Cotyledon cells of *Vigna mungo* seedlings use at least two distinct autophagic machineries for degradation of starch granules and cellular components

Kiminori Toyooka,1,2 Takashi Okamoto,1 and Takao Minamikawa1

1Department of Biological Sciences, Tokyo Metropolitan University, Tokyo, 192-0397 Japan
2Department of Infectious Diseases and Tropical Medicine, International Medical Center of Japan, Tokyo, 162-8655 Japan

α-amylase is expressed in cotyledons of germinated *Vigna mungo* seeds and is responsible for the degradation of starch that is stored in the starch granule (SG). Immunocytochemical analysis of the cotyledon cells with anti-α-amylase antibody showed that α-amylase is transported to protein storage vacuole (PSV) and lytic vacuole (LV), which is converted from PSV by hydrolysis of storage proteins. To observe the insertion/degradation processes of SG into/in the inside of vacuoles, ultrastructural analyses of the cotyledon cells were conducted. The results revealed that SG is inserted into LV through autophagic function of LV and subsequently degraded by vacuolar α-amylase. The autophagy for SG was structurally similar to micropexophagy detected in yeast cells. In addition to the autophagic process for SG, autophagosome-mediated autophagy for cytoplasm and mitochondria was detected in the cotyledon cells. When the embryo axes were removed from seeds and the detached cotyledons were incubated, the autophagosome-mediated autophagy was observed, but the autophagic process for the degradation of SG was not detected, suggesting that these two autophagic processes were mediated by different cellular mechanisms. The two distinct autophagic processes were thought to be involved in the breakdown of SG and cell components in the cells of germinated cotyledon.

Introduction

Seeds of higher plants accumulate storage materials such as carbohydrates and proteins in cotyledons or endosperms, and the reserves are degraded to supply carbon and nitrogen sources to further seedling growth (Bewley and Black, 1994). Endospermic monocotyledon seeds store the reserves in the endosperms, which are derived from the fertilization of a central cell in the ovule with a sperm cell from the pollen grains (for review see Russell, 1992). After or during the deposition of the reserves, cells in the endosperm die through possible programmed cell death, which is induced by ethylene, a plant hormone (Young et al., 1997). When the monocotyledon seeds are germinated, the degradation of storage materials in the endosperms is well ordered. In cotyledons of kidney bean and mung bean seedlings, the mobilization of reserves is initiated in the cells positioned furthest from the vascular bundle (VB),* and the degradation progresses toward the VB according to the progress of germination. On the other hand, the use of reserves first occurs in the cells nearest to the VB, and the breakdown progresses to the outer cotyledon cells in soybean and favabean seedlings (Bewley and Black, 1978).

*Abbreviations used in this paper: KV, KDEL-tailed cysteine proteinase-accumulating vesicle; LED, low electron density; LV, lytic vacuole; PSV, protein storage vacuole; SG, starch granule; VB, vascular bundle.

© The Rockefeller University Press, 0021-9525/2001/09/973/10 $5.00
The Journal of Cell Biology, Volume 154, Number 5, September 3, 2001 973–982
http://www.jcb.org/cgi/doi/10.1083/jcb.200105096
Such well-ordered degradation processes have been explained by the programmed cell death of plants (Greenberg, 1996; Pennell and Lamb, 1997). Senescence of higher plants is the final phase of a plant organ’s development, involves the active turnover and recapture of cellular materials for use in other organs (Nooden, 1988), and requires nuclear functions, suggesting it is an active and programmed process (Ness and Woolhouse, 1980). Cotyledons of dicotyledon seeds are leaves specialized for storage of reserves, and they change to senescence organs from vegetative organs at the stage of seed germination and subsequent seedling growth.

In cotyledons of Vigna mungo seeds, proteins and starch are stored in protein storage vacuoles (PSVs) and starch granules (SGs), respectively (Harris and Chrispeels, 1975; Minamikawa and Koshiba, 1979). Upon germination of the seeds, the storage proteins in the PSV are degraded by a papain-type proteinase, designated SH-EP (Mitsuhashi et al., 1986; Okamoto and Minamikawa, 1998) and the PSV is converted to a lytic vacuole (LV). Recently, it has been suggested that mass transport of proSH-EP from the endoplasmic reticulum (ER) to the PSV by ER-derived vesicles with a diameter of 200–500 nm mediates the characteristic/rapid conversion of PSV to LV in cotyledon cells (Toyouka et al., 2000). Although the degradation mechanism of storage proteins has been gradually resolved, the breakdown processes of another major storage material, starch, are still unclear. By biochemical analysis, α-amylase was identified as the enzyme that has a major role in the degradation of stored starch in the cotyledons of germinated V. mungo seeds (Koshiba and Minamikawa, 1981), but it remains open how the enzyme reaches SG or how degradation of SG occurs in the cotyledon cells. Since α-amylase has a signal peptide (Yamauchi et al., 1994) that should be recognized with signal recognition particles, the enzyme would enter the lumen of the ER (von Heijne, 1983) and thus is expected to be further transported to the vacuoles or secreted by the endomembrane system. This supposed intracellular localization of α-amylase indicates that the enzyme is not directly sorted to SG originating from plastides.

In this study, we first identified the intracellular localization of α-amylase in the cotyledon cells of V. mungo seedlings or embryo axis-removed (detached) seeds by immunocytochemical assays using affinity-purified anti–α-amylase antibody. The results obtained showing the vacuolar localization of α-amylase in the cotyledon cells led us to observe the ultrastructures of the cotyledon cells to see the interaction of the vacuoles with the SG. The SG was wrapped with the acidic cell compartment that would be formed by fusion of a de novo synthesized acidic vesicle and subsequently incorporated into the LV. In addition, a distinct autophagic process to that for SG was found to be involved in the degradation of cytoplasm and mitochondrion. We showed that at least two distinct autophagic processes function for the degradation of the SG and other cytoplasmic components in the cells of the germinating cotyledon.

Results
Expression of α-amylase in attached or detached cotyledons
We have previously reported that removal of the embryonic axes from V. mungo seeds had effects on expression of proteinase activity and degradation of storage reserves in cotyledons (Minamikawa, 1979; Yamauchi et al., 1994). When V. mungo seeds were allowed to germinate at 27°C in darkness, proteinase and amylase activities in the cotyledons (attached cotyledons) increased and reached a maximum level at 3 d after imbibition, and the amounts of storage proteins and starch gradually decreased during seed germination and subsequent seedling growth. When detached cotyledons (embryonic axes were removed from dry seeds) were prepared and incubated under the same conditions as above, mobilization of storage proteins and starch was not observed, and the proteinase activity remained at a low level. However, amylase activity appeared even in the detached cotyledons at an equivalent level to that in the attached cotyledons (Yamauchi et al., 1994). In this study, changes with time in amounts of a papain-type proteinase (SH-EP), α-amylase and an asparaginyl endopeptidase (VmPE-1; Okamoto et al., 1994) in the attached or detached cotyledons were analyzed by SDS-PAGE and immunoblotting with anti–SH-EP, α-amylase, or VmPE-1 antibody. In the attached cotyledons, these three hydrolases were synthesized de novo, and the amounts of these enzymes increased in V. mungo seeds within 4 d after imbibition (Fig. 1). In the detached cotyledons, expressions of SH-EP and VmPE-1 were markedly suppressed, but the expression level of α-amylase was almost the same as that in the attached cotyledons (Fig. 1). These results indicate that α-amylase is normally expressed even in detached cotyledon cells in which starch stored in SGs is intact (Minamikawa 1979; Yamauchi et al., 1994), and that α-amylase is not directly transported to SGs but to other cell compartment(s) in the cotyledon cells. Thus, to determine the intracellular localization of the enzyme, subcellular fractionation and immunocytochemical assays of cotyledon cells were conducted.

![Figure 1. Changes with time in amounts of SH-EP, α-amylase, and VmPE-1 in cotyledons of V. mungo seedlings (Attached cotyledons) or embryo axis-removed cotyledons of V. mungo seeds (Detached cotyledons). Attached or detached cotyledons were prepared as described in Materials and methods. 10 pairs of cotyledons were homogenized with 3 ml of 50 mM Tris-Cl (pH 7.4), and the homogenates were centrifuged at 15,000 g for 10 min. Supernatants (10 μl each) were analyzed by SDS-PAGE immunoblotting with anti–SH-EP, α-amylase, or VmPE-1 antibody.](image-url)
sorting of cotyledon cells with anti–zyme is localized in PSV without proteolytic processing of and microsomal fractions (Fig. 2 C), suggesting that the en-

KV dependent. In addition to the PSV, the LV was densely

fractionated into microsome and PSV fractions, and both fractions were separated by SDS-PAGE. Polypeptides in the gel were analyzed by Coomassie Brilliant blue staining (A), or by immunoblotting with anti–SH-EP antibody (B) or anti–α-amylose antibody (C). Bracket indicates the polypeptides derived from storage globulins. Arrowhead indicates α-amylose.

Figure 2. Subcellular distribution of α-amylose in V. mungo coty-

ledon cells. Microsome and PSV fractions were prepared from coty-

ledons of day 3 seedlings as described in Materials and methods.

Electroblots of dry seeds and day 3 cotyledons, microsomes, and PSV fractions (20 μg protein each) were separated by SDS-PAGE. Proteins in the gel were analyzed by Coomassie Brilliant blue staining (A), or by immunoblotting with anti–SH-EP antibody (B) or anti–α-amylose antibody (C). Bracket indicates the polypeptides derived from storage globulins. Arrowhead indicates α-amylose.

Intracellular localization of α-amylose in cotyledon cells

Cotyledon cells of day 3 dark-grown V. mungo seedlings were fractionated into microsome and PSV fractions, and both fractions were separated by SDS-PAGE. In the PSV fraction, the polypeptides around 50 kD that were derived from storage globulins (Okamoto and Minamikawa, 1998) were enriched (Fig. 2 A). When the proteins in the gel were analyzed by immunoblotting with anti–SH-EP antibody, proSH-EP of 43-kD (ER and/or KDEL-tailed cysteine proteinase–accumulating vesicle [KV] form) and 33-kD mature SH-EP (vacuolar form) were detected in microsome and PSV fractions, respectively (Fig. 2 B; Okamoto et al., 1994). This suggests that fractionations of the microsome and PSV from cotyledon cells were successfully conducted. Probing the blots with anti–α-amylose antibody resulted in detection of α-amylose with molecular mass of 44 kD in both the PSV and microsomal fractions (Fig. 2 C), suggesting that the enzyme is localized in PSV without proteolytic processing of the enzyme in PSV. By immunocytochemical analysis of the cotyledon cells with anti–α-amylose antibody, it was revealed that α-amylose is localized in both PSVs and LVs (Fig. 3 A–F), which is possibly converted from the PSV by fusion of KV (Toyooka et al., 2000). Fig. 3 A shows that α-amylose is localized in the PSV but not in the SG. Immunogold staining of the Golgi complex with anti–α-amylose antibody indicates that α-amylose is transported to the PSV through a Golgi complex–dependent pathway (Fig. 3, B and C). When cotyledon cells were double immunogold–stained with anti–α-amylose monoclonal antibody and anti–SH-EP monoclonal antibody, α-amylose and SH-EP were localized in the PSV and KV, respectively (Fig. 3 D), supporting the sorting of α-amylose is Golgi complex dependent but not KV dependent. In addition to the PSV, the LV was densely

immunogold labeled (Fig. 3 E). This suggests that α-amylose is transported to both the PSV and LV or sorted to the PSV before the conversion of PSVs to LVs occurs. When the detached cotyledons were incubated for 3 days and the coty-

ledon cells were analyzed with the same procedures, it was indicated that α-amylose is transported to the PSV also in the detached cotyledons (Fig. 3, F and G).

Breakdown of SG in LVs through autophagic process

Ultrastructural analyses of the cotyledon cells of normally germinated V. mungo seeds were conducted to observe how SG interacts with vacuoles to be degraded by α-amylose. A cotyle-

don of a day 3 seedling is composed of heterologous cells with respect to the amount of reserves in the cells. Cells positioned near a vascular bundle (VB) were filled with storage materials (Fig. 4 A, region I), the reserves were degraded mostly in the cells far from the VB (Fig. 4 A, region III), and middle phase cells between filled cells and empty cells were observed (Fig. 4 A, region II). In the cells filled with reserves (filled cells), the border between the SG and cytoplasm was clear, and the electron density of the PSV was high since the storage proteins were intact (Fig. 4 B). The electron density of the PSV became low when the degradation of proteins started (Fig. 4 C). In the same cells, a membranous structure surrounding SGs was observed, and some regions with low electron density (LED) were found (Fig. 4 C). The LED area around the SG was enlarged in the empty cells in which most reserves were degraded and the PSV was converted to an LV (Fig. 4 D). In addition, vesicles with similar density to the LV and LED regions were observed in the empty cells (Fig. 4 E). These vesicles would be formed/synthesized de novo, since such vesicles were not found in the filled cells (Fig. 4 B). An SG surrounded with the LED region interacted with the LV (Fig. 4 F), and membrane fusion between the LED area around the SG and LV was observed (Fig. 4 F). The SG was found to be in the inside of the LV, and the shape of the SG was not round (Fig. 4 G), suggesting that degradation of SGs in LVs results in a change of shape of the SGs. Fig. 4 H represents the immunogold image of degradation of an SG by α-amylose in an LV. A major part of α-amylose was found at the peripheral region of the SG, which was inserted into the LV (Fig. 4 H), suggesting the degradation of starch occurs at the peripheral area of SGs. In contrast to cells of attached cotyledons, conversion of PSVs to LVs was not observed, and SGs were not taken up into a PSV in the cells of detached cotyledons, which were incubated for 3 d (Fig. 4 I). In addition, neither the LED region around the SG nor the possibly de novo–synthesized vesicle with similar density to the LV was observed in the cells (Fig. 4 I). The degradation of the SG in LVs (Fig. 4, E–G) will indicate that the conversion of PSVs to LVs must occur before starch breakdown. By biochemical analyses for changes with time in amount of proteins and starch in the cotyledons of germinated V. mungo seeds, it has been revealed that the amount of proteins decreases in the cotyledons before starch breakdown (Minamikawa, 1979). The observation of degra-

dation of the SG in LVs supports the previous report, since degradation of storage proteins in PSVs results in PSV conversion to LVs. Next, SGs, cells containing SGs, and thick sec-

tions were prepared from the cotyledons of day 3 seedlings and subsequently stained with LysoTracker red, an acidic or-
ganelle-selective probe. Small foci stained with the probe were found around the SG in broken cotyledon cells (Fig. 5, A–D) and in cells of cotyledon sections (Fig. 5, E–H). In addition, SGs were found to be wrapped with the acidic cell compartment (Fig. 5, I and J) and to be in the inside of a putative vacuole (Fig. 5, K and L). These LysoTracker red–stained small foci and cell compartments wrapping SGs explain the character of de novo–synthesized vesicles and the LED region around the SG, which were observed in the ultrastructural analyses of the cotyledon cells. The de novo–synthesized vesicles shown in Fig. 4 E may correspond to the small foci (Fig. 5, B, D, F, and H); and the LED region (Fig. 4, D and E), to the LysoTracker red–stained cell compartment wrapping SGs (Fig. 5 J). This also suggests the possibilities that vesicles or small cell compartments with acidic pH fuse with SGs and that LED regions around SGs are built up by the fusion of such acidic vesicles/small cell compartments. When sections were prepared from detected cotyledons, which were incubated for 3 d and subsequently stained with the probe, no small foci were observed in the cells (Fig. 5, M–P). This is consistent with the result of ultrastructural observation, showing that neither de novo vesicle or LED region around SGs was detected in the cells of detached cotyledons (Fig. 4 I).

**Autophagosome-mediated autophagy in cotyledon cells**

In the course of the ultrastructural observation of the cotyledon cells, the autophagic process for cytoplasm and...
mitochondrion, which is distinct from that for SGs, was detected. Two autophagosomes containing cytoplasm with a double membrane were observed in the attached cotyledon cells, and mitochondria and cytoplasm appeared to be enclosed with double-membranous structure similar to that of the endoplasmic reticulum (Fig. 6 A). Autophagosome containing mitochondria and cytoplasm was fused with the LV (Fig. 6 B), and an autophagic body containing mitochondria was observed in LVs (Fig. 6 C). These results are consistent with the reports that vacuoles in the cotyledon cells of Vigna radiata function as autophagic organelles (van der Wilden et al., 1980; Herman et al., 1981). When the detached cotyledons were incubated at 27°C in darkness for 3 d and then analyzed by conventional electron microscopy, as shown in Fig. 6, A–C, autophagosomes and autophagic bodies were observed in the detached cotyledon cells (Fig. 6, D and E), although the conversion of PSV to LV did not occur (Figs. 4 I and 6, D and E). This indicates that autophagosome-mediated autophagy functions in detached cotyledons as well as attached cotyledons.

Discussion

α-Amylase was transported to the vacuoles via the Golgi complex in the cotyledon cells of V. mungo seedlings. This is consistent with the postulated intracellular localization of the enzyme (Yamauchi et al., 1994). In cultured rice cells, α-amylase was detected in the vacuoles and on cell walls, because α-amylase genes exist as a multigene family and there are several kinds of α-amylase in rice plant (Chen et al., 1994). In contrast, α-amylase of V. mungo is encoded by a single gene (Yamauchi et al., 1994), explaining the observa-
tion of clear localization of α-amylase only in the vacuoles of the cotyledon cells. The vacuolar sorting signals that have been identified (Chrispeels and Raikhel, 1992; Nakamura and Matsuoka, 1993) were not found in the amino acid sequence deduced from cDNA for α-amylase, indicating the possibility of the existence of an unidentified vacuolar targeting signal on the amino acid sequence of α-amylase of V. mungo.

Autophagic mechanisms have been intensively investigated in yeast, and at least two main autophagic machineries have been identified. First is macroautophagy: cytoplasm and/or mitochondria are sequestered into autophagosomes wrapped with a double membrane, and then the autophagosome fuses with vacuoles (Takeshige et al., 1992; Baba et al., 1994). Second is microautophagy, which was identified in the degradation process of the peroxisome in glucose-treated yeast cells. This autophagic process is proceeded by engulfment of the peroxisome by vacuoles and is called micropexophagy (Tuttle and Dunn, 1995; Sakai et al., 1998). Investigations for autophagy in plants have been mainly conducted with cultured cells, since removal of nutrients in culture medium often induces autophagy in the cultured cells (Chen et al., 1994; Aubert et al., 1996; Moriyasu and Ohsumi, 1996). Therefore, the study of autophagy related to plant development/senescence has been limited. This study indicates that two distinct autophagic processes function in the cotyledon cells of V. mungo seedlings for the degradation of reserves and cellular components. A model of two types of autophagies in a cotyledon cell is presented in Fig. 7. One autophagic process is the degradation of SGs. In the cotyledon cells, the SG is wrapped with an acidic cell compartment that is possibly built up by the fusion of small acidic vesicle synthesized de novo and subsequently incorporated into the LV that is converted from PSV by the fusion of KV.

Figure 5. LysoTracker red staining of partially broken cotyledon cells, SGs, or cotyledon sections. Cotyledon cells, SGs, and sections were prepared from day 3 attached or detached cotyledons and stained with LysoTracker red as described in Materials and methods. (A) Differential interface–contrast image of a broken cell. (B) Fluorescent image of A. (C) Differential interface–contrast image of a broken cell. (D) Fluorescent image of C. (E) Differential interface–contrast image of cells of a section from attached cotyledons. (F) Fluorescent image of E. (G) Magnified image of E. (H) Magnified image of F. (I) Differential interface–contrast image of an SG. (J) Fluorescent image of I. (K) Differential interface–contrast image of an SG. (L) Fluorescent image of K. (M) Differential interface–contrast image of cells of a section from detached cotyledons. (N) Fluorescent image of M. (O) Magnified image of M. (P) Magnified image of O. Bars: (A–D, G–L, O, and P) 20 μm; (E, F, M, and N) 50 μm.
As for de novo–synthesized vesicles with acidic pH, it is known that small vacuoles are synthesized de novo in the aleurone cells of germinated barley grains (Paris et al., 1996; Swanson et al., 1998; Sansebastiano et al., 2001). The vesicles in the cotyledon cells may correspond to the newly synthesized vacuoles. The degradation of SG in LV was observed by ultrastructural and immunocytochemical analyses of the cotyledon cells. However, we could not clearly identify how wrapped SGs were inserted into the inside of vacuoles. Two possibilities were suggested for the cellular mechanism of the insertion of SGs into LVs. A wrapped SG is further surrounded by several LVs and finally incorporated into the LV through membrane fusion between LVs (Fig. 4 E), or the membrane of the LED region around the SG is fused to that of the LV (Fig. 4 F), resulting in the insertion of SGs into the inside of LVs. It cannot be excluded that both mechanisms function synergistically for effective vacuolar degradation of LED-wrapped SGs. In yeast cells, the peroxisome is wrapped with thin or fragmented vacuoles at the first step of micropexophage, and subsequently the wrapped peroxisome is engulfed into the vacuole (Tuttle and Dunn, 1995; Sakai et al., 1998). Degradation of SGs may be proceeded by a mechanism analogous to micropexophage, since SG was also wrapped with acidic cell compartments.

The other autophagic machinery in the cotyledon cells is the macroautophagy that is mediated by autophagosome. In the autophagosome, mitochondria and cytoplasm were observed (Fig. 6, A–E), which corresponded to autophagic vesicles reported in the cotyledons of *V. radiata* (van der Wilden et al., 1980). These findings suggest that the cytoplasm and mitochondria in the cotyledon cells are sorted to the vacuoles via the autophagosome in a similar manner to those in yeast cells (Takeshige et al., 1992; Baba et al., 1994). The macroutaphagy was detected in both the attached and detached cotyledon cells, but the autophagic process for the degradation of SGs was observed only in the attached cotyledon cells. In the detached cotyledons, SH-EP was barely expressed, and storage proteins remained intact, resulting in no conversion of PSVs to LVs and in loss of SG degradation in LVs (Fig. 7).

The autophagic programmed cell death (PCD) detected in the cotyledon cells is different from PCD by hypersensitive response, the plant defence system against pathogens, or by differentiation of tracheary elements. PCD induced by hypersensitive response is highly similar to apoptosis (Goodman and Novacky, 1996), and that of the differentiation of tracheary elements is induced by tonoplast disruption and subsequent release of vacuolar hydrolases into the cytosol (Fukuda, 1997). Higher plants use the autophagic PCD for senescing organs rather than the apoptotic or hydrolase-releasing PCD, since hydrolysis of cellular materials in vacuoles does not damage the senescing cells, and withdrawal of cellular materials from the cells can be successfully achieved (Jones, 2000). In fact, two kinds of autophagic processes, micropexophage-like and autophagosome-mediated autophagies, were found to function in the germinated cotyledon cells, and a possible relationship between senescence and autophagy was indicated. Moreover, the ultrastructural analysis of senescing leaves also indicated that the autophagic PCD occurs in the senescing leaves of kidney beans (Mianikawa et al., 2001). Plants use vacuoles for storage of materials as well as hydrolysis of needless cellular components (for review see Herman and Larkins, 1999). In addition to these well-known functions of vacuoles, the autophagic vacuoles in senescing cells may be one way of the flexible uses of vacuoles by plants, since the turnover and re-
capture of cellular materials are exclusively developed in plants.

Materials and methods

Plant materials

V. mungo seeds were germinated on layers of wet filter paper at 27°C in darkness, and the cotyledons were collected on days 1 to 4 after imbibition. The cotyledons from the seedlings were used as attached cotyledons. To prepare detached cotyledons, embryo axes were removed from dry V. mungo seeds, and the embryo axis-removed cotyledons were incubated on wet filter paper at 27°C in darkness for 1–4 d.

Gel electrophoresis and immunoblotting

SDS-PAGE and immunoblotting were performed as described previously (Mitsuhashi and Minamikawa, 1989).

Preparation of antibodies

α-Amylase was purified according to Koshiba and Minamikawa (1981), and the purified enzyme (3 mg) was immobilized to 3 ml of ECH-Sepharose 4B (Amersham Pharmacia Biotech) according to the manufacturer's instructions. 25 ml of antiserum to α-amylase was precipitated by the addition of 12.5 ml of saturated ammonium sulfate solution, and the precipitate was dialyzed against PBS containing 0.1% sodium azide and used as anti-α-amylase antibody. Monoclonal and polyclonal antibodies against SH-EP (Toyooka et al., 2000) and anti-VmPE-1 antibody (Okamoto and Minamikawa, 1999) were prepared as described previously.

Immunocytochemistry and ultrastructural analysis

Cotyledons of 3-d-grown V. mungo seedlings or detached cotyledons incubated for 3 d were cut into ~1-mm³ cubes and fixed with 4% paraformaldehyde and 2% glutaraldehyde in 0.1 M potassium phosphate buffer (pH 7.4) for 4 h at 4°C. After fixation of the tissue pieces, they were dehydrated in a graded methanol series. Procedures for ultrastructural analysis were conducted as described previously (Hara-Nishimura et al., 1993). For immunocytochemical analysis, the dehydrated pieces were embedded in a hard formulation of LR White resin. Ultrathin sections mounted on nickel grids were conducted as described previously (Hara-Nishimura et al., 1993). For immunocytochemical analysis, the dehydrated pieces were embedded in a hard formulation of LR White resin. Ultrathin sections mounted on nickel grids (600 mesh; Electron Microscopy Sciences) were blocked with 10% fetal bovine serum in TBS (25 mM Tris-Cl, pH 7.4, 150 mM NaCl) for 10 min at room temperature. The sections were then labeled with affinity-purified antibody to α-amylase (diluted 1:1) or SH-EP (1:1) in TBS. After being washed with TBS, the sections were indirectly labeled with colloidal gold particles coupled to goat-anti-rabbit IgG or colloidal gold particles coupled to goat-anti-mouse IgG. The gold-labeled sections were then washed with TBS, rinsed in water, and stained with 4% aqueous uranyl acetate. The grids were examined and photographed with a transmission electron microscope (model 1010EX, JEOL) at 80 kV.

Subcellular fractionation of cotyledon cells, sectioning of cotyledons, and confocal laser scanning microscope

The microsome and PSV fractions were obtained from the cotyledons of day 3 V. mungo seedlings as described (Okamoto et al., 1994). To prepare the fraction containing SGs and partially broken cotyledon cells containing SGs, 50 pairs of day 3 cotyledons were gently ground in a mortar and pestle with 5 ml of 50 mM Hepes-KOH (pH 7.5) containing 0.5 M sucrose, 5
mM MgCl₂, 1 mM EDTA. The homogenate was filtered through a nylon mesh (150 μm in diameter), and the filtrate was allowed to stand for 10 min on ice for precipitation of SGs and broken cells containing SGs. The precipitate was resuspended in 5 ml of homogenization buffer, and the suspension was again allowed to stand for 10 min on ice. After the precipitate was resuspended with the buffer, LysoTracker red DND-99 (Molecular Probes) was added at the final concentration of 1 μM. After incubation for 15 min and subsequent washing twice, the samples were observed by confocal laser scanning microscopy (LSM 510, ZEISS) using a 543-nm He-lum-Neon laser for excitation and a 560-nm-long pass filter for the detection of fluorescence. Cotyledons from day 3 seedlings or detached cotyledons incubated for 3 d were transversally sliced by a razor blade into ∼0.5-mm-thick portions in the buffer (50 mM Hepes-KOH, pH 7.5, 0.5 mM sucrose, 5 mM MgCl₂, 1 mM EDTA). The sections were washed with the buffer and subsequently incubated in the buffer containing 1 μM LysoTracker red DND-99 for 10 min. After washing the sections three times, the samples were observed by confocal laser scanning microscopy as described above.

We thank Dr. Yoshihori Ohsumi, Dr. Kenji Noda, and Mr. Hideki Hanaka for their critical reading of the manuscript and useful discussions and suggestions. We are grateful to Dr. Teruo Kikaike for his assistance on conducting laser scanning microscopic observations.

This work was supported in part by Grants-in-Aid for Scientific Research (12740441) from the Ministry of Education, Science and Culture of Japan.

Submitted: 21 May 2001
Revised: 5 July 2001
Accepted: 16 July 2001

References


San Diego, CA. 1–50.


Autophagies in cotyledon cells of germinated seeds | Toyooka et al. 981

Plant

Cell


Cell. 119:301–311.


