Regulation of Lithospermic Acid B and Shikonin Production in Lithospermum erythrorhizon Cell Suspension Cultures

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Cell suspension cultures of Lithospermum erythrorhizon produced a large amount of lithospermic acid B, a caffeic acid tetramer, as well as shikonin derivatives (each ca. 10% of dry wt.) when cultured in shikonin production medium M-9. Various culture factors for increasing the production of lithospermic acid B were investigated. Lithospermic acid B production was inhibited by 2,4-D or NH4+, whereas it was stimulated by Cu2+. These regulatory patterns were similar to those for the production of shikonin derivatives in these cell cultures, suggestive of close relations and similar metabolic regulation between the production of these compounds. Cultivation under light illumination, however, showed that these metabolisms were independently regulated. In particular, blue light showed a stimulatory effect on lithospermic acid B production, while shikonin production was strongly inhibited, indicative of an effective condition for lithospermic acid B production.

Key words Lithospermum erythrorhizon; plant cell culture; lithospermic acid B; shikonin; light; nitrogen source

Caffeic acid oligomers such as rosmarinic acid and lithospermic acid B (LAB) are distributed in plants of Labiatae and Boraginaceae. Among these oligomers, LAB, the caffeic acid tetramer, has a variety of attractive pharmacological activities such as antioxidant and radical scavenging, improvement of renal disease, hypotensive, improvement of myocardial infarction, amplification of beating of myocardial muscles, anti-hepatitis, and aldose reductase inhibitory activity. To utilize LAB as a medicinal resource, more than 30 plant sources were surveyed and only two medicinal plants, Salvia officinalis and Lithospermum erythrorhizon Sieb. et Zucc., were found to contain this substance in an appreciable amount. Many attempts to produce this compound in high quantities using cell or hairy root cultures have been unsuccessful.

Recently, we found that L. erythrorhizon cell-suspension cultures, which were established for the industrial production of shikonin, produced four caffeic acid oligomers, rosmarinic acid, LAB, a monoglucoside of LAB, and (+)-rabdosinin. In particular, the production of LAB in the cultured cells was highly stimulated in shikonin production medium M-9, reaching almost the same amount as that of shikonin (LAB: ca. 6%–10% of dry wt, and total shikonin derivatives: ca. 6%–12% of dry wt.). Since both LAB and shikonin are formed through a common phenylpropanoid pathway (Chart 1), the counterbalance between two metabolic routes either to LAB or to shikonin would be regulated in L. erythrorhizon cells, suggesting that the selection of suitable regulatory factors would result in higher production of LAB. However, the metabolic linkage and the regulatory mechanism for the biosyntheses of phenylpropanoid-derived compounds of diverse types in L. erythrorhizon cell cultures remain to be clarified. In this study, we investigated the critical regulatory factors to control these two biosynthetic pathways separately and to produce LAB efficiently in the culture system of L. erythrorhizon.
to be a storage form of PHB, a biosynthetic precursor of shikonin, was almost constant during the entire culture period (Fig. 1A). In M-9 medium, LAB production increased rapidly after inoculation and resulted in a linear increase toward the end of the culture period, reaching 10 mg/g fresh wt. on day 21 (Fig. 1B). Unlike the production pattern of LAB, the production of shikonin needed a lag phase of 4 d after inoculation and the level reached 9 mg/g fresh wt. on day 21. The production of PHBOG was inversely proportional to that of shikonin, and only a trace amount of PHBOG was detectable to the end of the culture period.

Effects of Chemical Modulators in Shikonin Production on LAB Production

A number of modulators in shikonin production have been revealed in extensive studies made so far (for a recent review see ref. 34). In particular, shikonin production is clearly enhanced by the supplementation of Cu²⁺, but strongly inhibited by either NH₄⁺ or 2,4-D. We examined the effects of such shikonin production modulators on LAB production. As shown in Fig. 2, contrary to our expectations, 2,4-D and NH₄⁺, strong inhibitors of shikonin production, also inhibited LAB produc-

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**Fig. 1.** Time Courses of Cell Growth and Production of Secondary Metabolites in *L. erythrorhizon* Cells Cultured in M-9 Medium (A) or M-9 Medium (B)

Cells (1 g) were inoculated in a 100-ml flask containing 30 ml of medium and cultured for 3 weeks in the dark. Values are means of triplicate results, and bars show standard errors.

**Fig. 2.** Inhibitory Effects of 2,4-D (A) or NH₄Cl (B) on Phenylpropanoid-Derived Secondary Metabolites in *L. erythrorhizon* Cells Cultured in M-9 Medium (30 ml)

2,4-D or NH₄Cl was added to the medium before autoclaving. Values are means of triplicate results, and bars show standard errors.
Shikonin production in M-9 medium in a dose-dependent manner. At 2,4-D 1 mM or at NH₄⁺ 1 mM at which shikonin production was completely inhibited, the LAB level declined to that in LS medium-cultured cells. Under these culture conditions, the level of PHBOG was restored to that in the cells cultured in LS medium (Fig. 1A). On the other hand, the supplementation of Cu²⁺, a potent stimulator of shikonin production, also stimulated the production of LAB. Figure 3 shows the effect of added Cu²⁺ on LAB production in Cu²⁺-free M-9 medium. Both LAB and shikonin production was enhanced by the addition of Cu²⁺. However, the LAB level nearly reached a plateau at concentrations higher than Cu²⁺ 1 mM, whereas shikonin production was stimulated up to Cu²⁺ 10 mM in a dose-dependent manner.

LAB production was also affected by the NO₃⁻ concentration. When nitrogen sources in LS medium were replaced with NO₃⁻, lower concentrations of NO₃⁻ tended to result in more LAB production (data not shown). This effect was reinforced by the addition of Cu²⁺ 1.2 μM (Fig. 4). At NO₃⁻ 6.7 mM and Cu²⁺ 1.2 μM, the amount of LAB reached to 71% (5.3 mg/g fresh wt.) of that in M-9 medium cells. On the other hand, only a trace amount of shikonin production (0.2 mg/g fresh wt., 3% of that in M-9 medium) was observed under the same conditions.

PO₄³⁻, which influences the production of many secondary metabolites including polyphenols in plant cell cultures, did not affect the production of LAB and shikonin in L. erythrorhizon cells cultured in either LS or M-9 medium (ranging from 0.12 to 1.25 mM, data not shown).

Effect of Light on LAB Production Light is a physiological regulatory element in shikonin biosynthesis. White or blue light strongly inhibits shikonin production by suppressing the gene expression of PHB geranyltransferase, a key enzyme in shikonin biosynthesis, as well as 3-hydroxy-3-methylglutaryl-coenzyme A (HMG-CoA) reductase, an enzyme responsible for the formation of the geranyl side chain of shikonin. As shown in Fig. 5, LAB production was slightly stimulated by white light irradiation compared with that in cells cultured in the dark, whereas shikonin production was completely inhibited. It was noteworthy that cultivation under white light irradiation resulted in a high accumulation of PHBOG (7.4 mg/g fresh wt.), which was about equal to that of shikonin in the dark-grown controls (8.9 mg/g fresh wt.). When the cells were cultured under blue light, PHBOG was only 2.5 mg/g fresh wt., whereas the LAB content reached 12.1 mg/g fresh wt. (170% of the dark-grown controls). LAB production was also stimulated under red or green light (157% and 156% of the dark-grown controls, respectively). Under these conditions, shikonin production was not as inhibited (69% and 55% of the dark-grown controls, respectively), and the PHBOG content remained at a low level.

Discussion It is well known that shikonin derivatives are produced on industrial scale from L. erythrorhizon cell cultures. In the present study, we demonstrated that LAB was produced almost specifically in a higher yield than that of shikonin, which was achieved by cultivation in the dark, in L. erythrorhizon cells by cultivation under blue light irradiation.

It has been demonstrated that the enzyme susceptible to
inhibition by blue or white light in shikonin biosynthesis is PHB geranyltransferase. Furthermore, Gaissier and Heide reported that white light irradiation increased the activity of PHB-O-glucosyltransferase in *L. erythrorhizon* cells, while blue light did not affect it. No shikonin in cells cultured under white or blue light was produced. This led us to expect that the exclusive utilization of the phenylpropanoid unit under light irradiation could lead to higher production of LAB. To assess this assumption, the efficiency of utilization of the phenylpropanoid unit in either LAB or shikonin biosynthesis and in PHBOG formation was stoichiometrically analyzed in *L. erythrorhizon* cells cultured under different light conditions (Fig. 6). Light irradiation did not increase the production of the phenylpropanoid unit but led to increased production of caffeic acid derivatives. The production of LAB was less affected by white light, although greater accumulation of PHBOG was observed. Meanwhile, cultivation under blue light illumination increased the flow of the phenylpropanoid unit into the formation of LAB, presumable owing to the inhibition of PHB geranyltransferase and the low activity of PHB glucosyltransferase. PHB, which was assumed to be cytotoxic, was not detectable under any culture conditions employed in the present study, as reported in previous papers. There might be a negative feedback regulation in the supply of PHB as a biosynthetic intermediate, although the conversion of 4-coumaric acid to PHB has not yet been completely clarified.

Under red or green light irradiation, LAB production was also stimulated but shikonin production was not completely inhibited (Fig. 5). These results might indicate that light qualities regulate LAB formation in different manners and also have independent effects on the biosynthesis of both compounds in *L. erythrorhizon* cells. The stimulation of 4-coumarate CoA ligase expression by light in *L. erythrorhizon* cells may also contribute to the increase in LAB production, because this enzyme is responsible for LAB biosynthesis (Chart 1).

The inhibitory effects of 2,4-D and NH$_4^+$ as well as the stimulatory effect of Cu$^{2+}$ on LAB and shikonin production were also demonstrated in this study (Figs. 2, 3). These data suggest that common earlier steps in the biosynthetic pathways of shikonin and LAB are controlled by similar regulation mechanisms. Cells cultured in modified LS medium containing nitrate and Cu$^{2+}$ at the same concentrations as those in M-9 medium (NO$_3^-$ 6.7 mM and Cu$^{2+}$ 1.2 μM) produced some LAB (ca. 70% of that observed in M-9 medium), while they resulted in the poor production of shikonin (3% of the yield in M-9 medium) (Fig. 4). These results suggest that nitrate and Cu$^{2+}$ stimulate the production of LAB but not of shikonin. Thus we have found an effective, although not yet sufficient, condition for high production of LAB. On the other hand, the production of (+)-rhabdosin, another caffeic acid tetramer presumably formed from rosamericin acid like LAB (see Chart 1) was almost unaffected by the modulators connected with LAB production (data not shown). In intact *L. erythrorhizon* plants, LAB is mostly accumulated in the main roots whereas (+)-rhabdosin is mainly found in the aerial parts as well as in fibrous roots. The different distribution pattern of these two caffeic acid tetramers in intact plants might result in the different response to the above modulators in cultured cells. Further investigation of culture components as well as further biochemical and molecular biological studies on the enzymes responsible for LAB biosynthesis will contribute to more effective production of LAB in this cell culture.

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**References**

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