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ORIGINAL PAPER

Ectopic overexpression of the aluminum-induced protein gene from *Panax ginseng* enhances heavy metal tolerance in transgenic *Arabidopsis*

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Abstract Aluminum (Al), one of the most abundant metals in agricultural soils, significantly limits crop growth and productivity in acidic soil by inhibiting root elongation. Al ions, especially Al^{3+}, have a toxic effect on both plant and animal cells under low-pH conditions. We first isolated and characterized *aluminum-induced protein* (*AIP*) cDNA from a 4-year-old root of *Panax ginseng* Meyer. This cDNA encodes an open reading frame of 711 bp with a deduced amino acid sequence of 236 residues. The calculated molecular mass of the mature protein is approximately 58.9 kDa with a predicated isoelectric point of 5.13. The *Panax ginseng AIP* (*PgAIP*) contains a domain also present in *wheat aluminum-induced protein 7* (*Wali7*) and shares homology with the AIPs of other species, including Codonopis and *Arabidopsis*. The *PgAIP* gene was abundantly expressed in the plant's leaves and was up-regulated by Al exposure. The functional role of *PgAIP* in Al tolerance was further validated through its overexpression in *Arabidopsis*. Transgenic *Arabidopsis* plants overexpressing the *PgAIP* gene showed enhanced Al tolerance in terms of root growth when compared to wild-type plants, suggesting *PgAIP* is important in plant defense against Al toxicity. Confocal analysis of CFP-tagging PgAIP in *Arabidopsis* showed subcellular localization in the plasma membrane. Our results suggest that *PgAIP* in the plasma membrane plays an important role in the protection of plant cells against heavy metal exposure.

Keywords Aluminum-induced protein · Gene expression · Heavy metal · *Panax ginseng* · Wali7

Abbreviations

AIP	Aluminum-induced protein
Al	Aluminum
cDNA	Complementary DNA
EST	Expressed sequence tag
ORF	Open reading frame
qRT–PCR	Quantitative reverse transcription–polymerase chain reaction
HM	Heavy metal
Wali7	Wheat aluminum-induced protein 7

Introduction

In many parts of the world, agricultural soils are contaminated with heavy metals that pose a serious health hazard to humans, animals, plants, and soil microorganisms (Ghnaya et al. 2010). Aluminum (Al) is the most abundant metal (Goodwin and Sutter 2009), composing approximately 7.5 % of the elements in the earth' crust (Haug and Foy 1984). Although Al is an important mineral in plant growth and development (Kim et al. 2004), it has a toxic effect under low-pH conditions (Ezaki et al. 2004). Present in over 50 % of the world's arable lands (von Uexküll and Mutert 1995), Al toxicity in acidic soils is a major factor limiting crop growth and productivity by inhibiting root elongation (Kochian 1995; Goodwin and Sutter 2009). The inhibition of root elongation impairs the uptake of water

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