Leghemoglobin green derivatives with nitrated hemes evidence production of highly reactive nitrogen species during aging of legume nodules

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Globins constitute a superfamily of proteins widespread in all kingdoms of life, where they fulfill multiple functions, such as efficient O_2 transport and modulation of nitric oxide bioactivity. In plants, the most abundant Hbs are the symbiotic leghemoglobins (Lbs) that scavenge O_2 and facilitate its diffusion to the N_2-fixing bacteroids in nodules. The biosynthesis of Lbs during nodule formation has been studied in detail, whereas little is known about the green derivatives of Lbs generated during nodule senescence. Here we characterize modified forms of Lbs, termed Lb*a*$_m$, Lb*c*$_m$, and Lb*d*$_m$, of soybean nodules. These green Lbs have identical globins to the parent red Lbs but their hemes are nitrated. By combining UV-visible, MS, NMR, and resonance Raman spectroscopies with reconstitution experiments of the apoprotein with protoheme or mesoheme, we show that the nitro group is on the 4-vinyl. In vitro nitration of Lb*a* with excess nitrite produced several isomers of nitrated heme, one of which is identical to those found in vivo. The use of antioxidants, metal chelators, and heme ligands reveals that nitration is contingent upon the binding of nitrite to heme Fe, and that the reactive nitrogen species involved derives from nitrous acid and is most probably the nitronium cation. The identification of these green Lbs provides conclusive evidence that highly oxidizing and nitrating species are produced in nodules leading to nitrosative stress. These findings are consistent with a previous report showing that the modified Lbs are more abundant in senescing nodules and have aberrant O_2 binding.

Globins constitute a superfamily of proteins widespread in bacteria, protozoa, fungi, plants, and animals (1). Not surprisingly, they are structurally and functionally diverse. Flavohemoglobins of bacteria and yeast are chimeric Hbs with heme and FAD reductase domains, and are involved in nitric oxide (NO•) metabolism because of their high NO• dioxygenase activity (2). In humans and other vertebrates, Hb and Mb play key roles in efficient O_2 transport and storage but are also involved in NO• homeostasis, whereas the recently discovered neuroglobin and cytoglobin might assist in O_2 transport to the mitochondria and act as NADH oxidases and O_2 sensors (2, 3). Plants contain up to three types of Hbs: symbiotic, nonsymbiotic, and truncated. Symbiotic Hbs, which include leghemoglobins (Lbs) of legumes and some Hbs of actinorhizal plants, scavenge O_2 and facilitate its diffusion to the N_2-fixing microbial symbionts in nodules (4). Nonsymbiotic Hbs are further classified into two groups based on phylogeny and O_2-binding properties. Class 1 Hbs are expressed at ∼100 nM in most plant tissues, display extremely high affinity for O_2, and participate in NO• metabolism and in the maintenance of cell energetics under hypoxia (5–7), whereas class 2 Hbs have similar O_2 affinities to Lbs but unknown function (8). Plant truncated Hbs resemble their bacterial counterparts in having a 2/2 helical sandwich secondary structure instead of the canonical 3/3 structure of other Hbs, and have not yet been assigned any role (1).

Legume nodules are an interesting model to study Hb function and regulation as they express the three types of plant globins (9). Specifically, Lbs are present at concentrations of 2–3 mM and maintain a free O_2 concentration of 20–40 nM in the cytosol of host cells (10). This range of O_2 concentration permits an adequate supply of ATP for N_2 fixation but avoids nitrogenase inactivation (4). In nodules, Lbs are usually found as multiple components, the relative proportions of which vary with age (11). In soybean nodules, there are four major components (a, c_1, c_2, c_3), encoded by different genes, and four minor components (b, d_1, d_2, d_3), originated by posttranslational modification (11, 12). Considerable progress has been made on elucidating the regulatory pathways of Lb biosynthesis (13, 14, and references therein), whereas the mechanisms implicated in its degradation are virtually unknown. In animals and plants, the conversion of heme to biliverdins is catalyzed by heme oxygenase (15, 16), but can be carried out also nonenzymatically (coupled oxidation) at pH 7.5 in the presence of ascorbate and O_2 (17, 18). In plants, biliverdin-like pigments perform important functions in photosynthesis and photomorphogenesis (15) and are also associated with a decrease of N_2 fixation activity and Lb content in senescent nodules (17, 19). Legume nodule senescence, whether natural or stress-induced, is a complex and poorly studied process, with potential agricultural and ecological relevance as it limits the functional lifespan of nodules, and thereby N_2 fixation (19–21).

The green proteins derived from Lb in nodules have not yet been characterized. More than 60 y ago, Virtanen and Laine (17) reported the presence in legume nodules of a green pigment similar to animal choleglobin, and proposed that it was generated from Lb through the breaking of the tetrapyrrole ring without the release of Fe. Much more recently, a different type of green proteins was isolated from soybean nodules (22). The "modified" proteins, termed Lb*a*$_m$ and Lb*c*$_m$, derive from Lb*a* and Lb*c* (22). Spectroscopic analysis of Lb*a*$_m$, purified by isoelectric focusing (IEF), revealed that this protein has an amino acid sequence identical to Lb*a* but an unknown alteration of

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the tetrapyrrole ring (22, 23). Identification of the heme modifications in Lba_m and Lbc_m is important because they are increasingly produced during nodule senescence and exhibit aberrant binding to O_2 (24). In this article we show that soybean Lba_m and Lbc_m have a 4-nitrovinyl in their heme groups, and that these modified hemoproteins can be reproducibly generated in vitro by exposure of functional Lb*a* and Lb*c* to nitrite (NO_2^-) via reactive nitrogen species (RNS). This finding reveals that Lbs are a target of nitration in vivo and demonstrates the production of powerful oxidant and nitrating species in nodules, particularly during senescence.

Results

Purification and Identification of Lb Components and Modified Forms. The major Lb components and their derivatives were purified from soybean nodules by ammonium sulfate fractionation followed by several chromatographic steps (22). Fractions containing Lbs were further purified by IEF using a narrow range of pH, which allowed us to separate Lb*a*, Lbc_1, and Lbc_2+c_3 from the corresponding green derivatives. It was not possible to fully resolve Lbc_2 and Lbc_3, as their pI values differ by only 0.01 units (11), and the same problem was encountered with the respective modified forms Lbc_{2m} and Lbc_{3m}. To confirm the identification of Lbs and their modified forms and to detect possible chemical modifications in the polypeptides, all bands containing Lbs were carefully excised from the IEF gels and the proteins were eluted and analyzed by MALDI-TOF/MS. The molecular masses of the apoproteins of Lb*a*, Lbc_1, Lbc_2, and Lbc_3, as well as those of their respective modified forms, were found to be 15,241, 15,256, 15,393, and 15,451 Da, respectively, which matched $\pm$ 1 Da those predicted from the amino acid sequences excluding the initial Met. The lack of this Met residue is common in Lbs, which usually have Gly or Val at the N terminus (25). We also purified two fractions containing the Lb*d* and Lbd_m components. The molecular masses of the apoproteins of Lbd_1, Lbd_2, and Lbd_3 were found to be 15,299, 15,436, and 15,492 Da, which exceed by 42 $\pm$ 1 Da those of Lbc_1, Lbc_2, and Lbc_3, respectively. This mass difference was in agreement with the presence of an N-terminal acetylation as confirmed by MALDI-TOF peptide mass fingerprinting of the tryptic digests. As occurred for the other Lb-modified forms, the apoproteins of the Lbd_m derivatives have identical molecular masses to those of the parent proteins. We thus conclude that all four minor Lb components of soybean arise from the major components by N-terminal acetylation, and that all of the green Lb derivatives are affected in the hemes and not in the globins.

Structural Elucidation of Modified Hemes. Purified Lb*a* and Lbc_m from soybean nodules were used for comparative structural analyses of the protoheme and the modified heme (Fig. S1) by using UV-visible, MS, NMR, and resonance Raman (RR) spectroscopies. In some cases, Lb*c* was also used as a model because the spectral properties of Lb*a*, Lbc_1, and Lbc_2+c_3 are almost identical. The major features of the UV-visible spectra of Lb*a* and Lbc_m, as well as those of some representative complexes, are shown in Table S1. In sharp contrast to the ferric form of typical Lbs, ferric Lbc_m exhibits a Soret band at 389 nm with a shoulder at 436 nm, and a charge-transfer absorption band at 615 nm. The pyridine hemochrome spectrum of Lbc_m was identical to that of Lba_m (23), exhibiting prominent absorption bands at 553 nm (α-band) and 522 nm (β-band) and a new peak at 580 nm. However, the spectra of the deoxyferrous forms or of the ferrous complexes with NO• or nicotinate were similar for Lb*a* and Lbc_m. These data indicate that the heme of Lbc_m is not cleaved and still retains the capacity to bind ligands, but also that it is chemically affected on the tetrapyrrole ring itself or on the vinyl groups.

To determine precisely the nature of the modification, heme structures were exhaustively analyzed by MS^n fragmentation with microelectrospray ionization-linear ion trap and with Fourier transform-ion cyclotron mass spectrometers. Initial analyses were performed on the isolated modified hemes but they were relatively unstable. Consequently, the whole proteins were directly subjected to MS analysis, which was optimized for maximal yield of the heme molecular ions. The hemes of Lb*a*, Lb*c*, and Lb*d* had a *m/z* 616, as expected for protoheme, whereas those from Lba_m, Lbc_m, and Lbd_m had a *m/z* 661. High-resolution MS of these molecular ions proved that the 45-Da difference was a result of the insertion of a NO_2 group (Table S2). The molecular ions were extensively fragmented (MS^2 to MS^4) and the elemental compositions of the most relevant fragments elucidated by high-resolution MS. These analyses revealed that one propionic group, at least the α-carbon and carboxyl of the other propionic group, and at least three Me groups of the tetrapyrrole, were intact in the modified hemes (Table S2). Notably, the fragmentation patterns up to MS^4 of the Lba_m, Lbc_m, and Lbd_m hemes were identical, thus confirming, together with the UV-visible spectroscopy data, that all of them bear a NO_2 group.

Further structural information on the modified hemes was obtained by ^{1}H NMR spectroscopy using the ferric-cyano forms of the unmodified Lb*a* and the modified Lbc_m proteins, rather than the free hemes, to avoid problems encountered with instability and artifactual chemical alteration during heme isolation from Lbc_m. As a standard for comparison, the Lb*a* sample was found to have a 1D ^{1}H NMR spectrum with identical proton signals to that already published (26), but with assignments, made via the Water-Eliminated Fourier Transform-Nuclear Overhauser and Exchange SpectroscopY (WEFT-NOESY) spectrum (Fig. S2), which showed the heme to be reversed in vinyl substituent placement within the protein, as reported for the nicotinate complex (27). All resonances of the Lb*a* heme were assigned except for those of the 4-vinyl group and *meso*-γ-H (Table S3), the resonances of which were buried in the protein resonance region. Because the sample of Lbc_m protein was relatively small and composed of a mixture of Lbc_{1m} and Lbc_{2m}+c_{3m} (see above), it was not possible to assign as many of the heme resonances of these Lbc_m isoproteins (Fig. S3). The chemical shifts of all of the heme Me resonances of the two major species of the Lbc_m sample were changed by the heme modification, in part because the greater size of the modified substituent changed the heme seating by about 7° (28). The chemical shifts of the 2-vinyl group and the 6-propionate α- and β-protons were not significantly modified, nor were those of the 7-propionate α-protons. The 7β protons could not be unambiguously assigned in this dilute sample; however, because the 7α protons do not show large chemical shifts relative to those of Lb*a*, the modification cannot be at the 7β carbon. Thus, the modification of the heme appears to be at the 4-vinyl substituent. Unfortunately, none of the protons of the 4-vinyl group of Lbc_m could be identified, and thus our study was complemented with RR spectroscopy and reconstitution experiments.

The RR spectra of ferric Lb*a* and Lbc_m are compared in Fig. S4. The mode notations and the band assignments are based on refs. 29–31. The high-frequency regions of RR spectra reveal the binding of a NO_2 group to the protoheme of Lbc_m, with a signature at 1,320 cm^{-1}, specific of a nitroaromatic group (30). In the mid-frequency and low-frequency RR spectra, the frequencies of modes involving the peripheral vinyl and Me groups are significantly modified, further indicating binding of a NO_2 group to a vinyl (29, 31). In-plane and out-of-plane porphyrin modes show changes in frequency in accordance with an increased porphyrin distortion upon nitration (32). This increased protoheme distortion likely originates from a minimization of the steric contacts between the nitrovinyl and its adjacent Me groups.

Reconstitution of Lbs with Mesoheme and in Vitro Nitration. The possibility that the nitrated heme originated by a substitution of a proton by NO_2 on a vinyl group was suggested by previous work on nitriMb (33) and nitriHb (34, 35). These green Mb and

Hb derivatives contain a 2-nitrovinyl group and are generated in vitro by exposing the proteins to excess NO_2^-. Thus, we prepared apoLb*a* and apoLb*c*, reconstituted the holoproteins with protoheme or mesoheme (heme with ethyl groups replacing vinyls), and attempted to nitrate them (Fig. 1). The apoLb reconstituted with protoheme yielded green protein products having modified visible spectra and heme groups with *m/z* 661, which had identical fragmentation patterns to the hemes of nitriMb, Lba_m, Lbc_m, and Lbd_m. In contrast, the apoLb reconstituted with mesoheme remained unaffected after the $NaNO_2$ treatment, based on the IEF, Soret and visible spectra, RR, and MS analyses of the protein. The MS analysis showed a molecular ion of *m/z* 620, characteristic of the Fe-mesoporphyrin lacking NO_2 (Fig. 1). Taking these results together with the MS, NMR, and RR data, we conclude that the NO_2 group of the modified Lb hemes is on the 4-vinyl and that several structural isomers are produced by nitration of the protoheme. To substantiate the presence of several isomers of Lb hemes, Lb*a* purified from soybean nodules was nitrated with $NaNO_2$ at pH 7.0 or 5.5 at room temperature and the resulting proteins were resolved on preparative IEF gels (Fig. 2). Nitration was faster at pH 5.5 than at pH 7.0, being completed within ~1 and ~2 d, respectively, when ~200 μM Lb and ~200 mM NO_2^- were used. At pH 5.5, heme nitration required ~3 d to complete with ~20 mM NO_2^- and was far from completion after 5 d with ~2 mM NO_2^-.

Typically, six Lb*a* derivatives were produced, four of which (Lb*a*N2, Lb*a*N4, Lb*a*N5, and Lb*a*N6) were green (Fig. 2). Lb*a*N6 was low abundant and could not be studied further. All other derivatives had pyridine hemochromes, with a 580-nm band that is absent in unmodified Lbs (Table S1). The ferric aquo forms had Soret bands at 391–403 nm, with shoulders at 433–436 nm, as well as a charge-transfer band at 615 nm. The Soret bands of Lb*a*N4 and Lb*a*N5 showed the closest match to those of Lba_m or Lbc_m (Table S1). This similarity was confirmed by RR spectroscopy (Fig. S5). Based on the relative intensity of the bands at ~1,320 and 1,373 cm^{-1}, the spectrum of the Lb*a*N4 is the closest one to that of Lbc_m. Furthermore, in the 1,400–1,700 cm^{-1} region, the spectra of Lbc_m and Lb*a*N4 were most similar in terms of band shape and frequency. This similarity was also found in the mid- and low-frequency regions. Thus, we conclude that Lb*a*N4 has an identical modified heme to Lba_m or Lbc_m.

All Lb*a*N derivatives had hemes with a *m/z* 661 and identical high-order fragmentation profiles. Similarly, all of the apoLb*a*N derivatives were found to have a molecular mass of 15,240 ± 1 Da, as determined by MALDI-TOF/MS, and hence do not bear any modification in their amino acid residues. Consequently, the in vitro nitration of Lbs with excess NO_2^- can reproducibly generate the modified Lbs found in nodules, as well as several isomers of nitrated hemes.

Involvement of RNS in Heme Nitration. Both NO_2^- and NO• are unable to directly nitrate proteins, whereas other RNS derived therefrom can do it in vitro and presumably in vivo. These oxidant and nitrating RNS include peroxynitrite ($ONOO^-$), nitrogen dioxide radical (NO_2•), and nitronium (NO_2^+) salts (36–38). Experiments were carried out with recombinant or purified soybean Lb*a* and with equine Mb for comparative purposes to elucidate the nature of the RNS and the pathways involved in heme nitration. This task is complicated because $ONOO^-$, when present as peroxynitrous acid (ONOOH, pK_a= 6.8), can undergo homolytic cleavage to NO_2• and hydroxyl radical (•OH), and

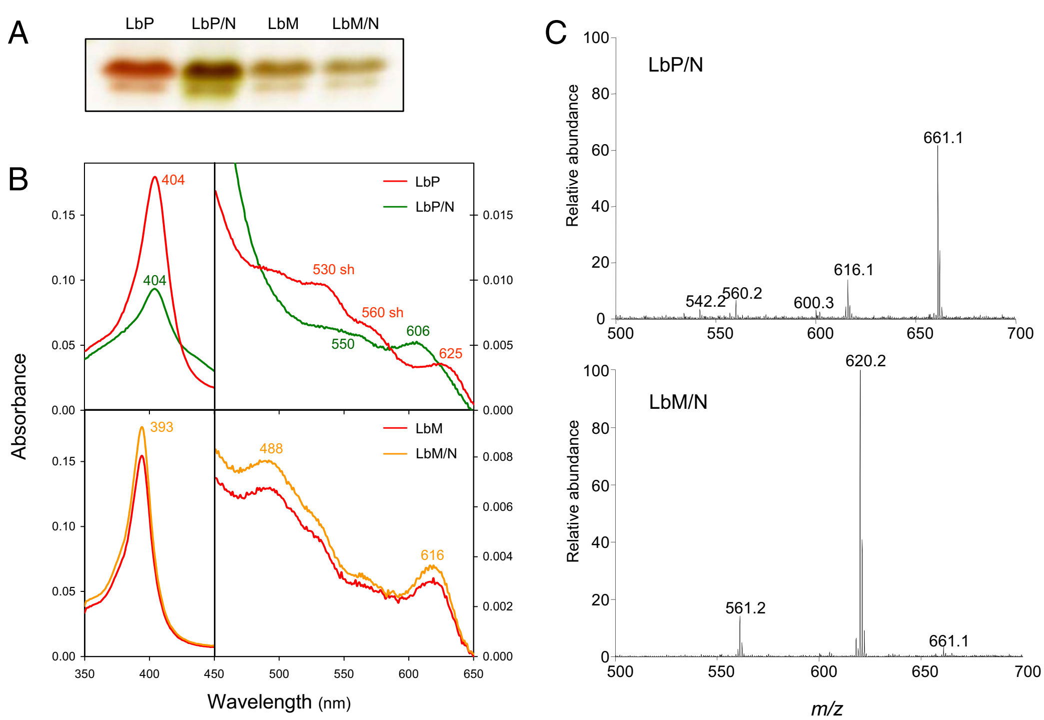

Fig. 1. In vitro reconstitution and nitration of Lb. (*A*) ApoLb*c* was reconstituted with either protoheme (LbP) or mesoheme (LbM) and treated for 24 h at pH 6.5 with a 1,000-fold excess of $NaNO_2$. The products (LbP/N and LbM/N) were loaded on an analytical IEF gel and let to proceed until separation of Lbc_1 (*Upper* band) and Lbc_2+c_3 (*Lower* band). Green nitrated derivatives were formed from the Lb bearing heme with vinyls (LbP/N) and not from the Lb bearing heme with ethyl groups (LbM/N). (*B*) Soret and visible spectra of aliquot samples of the proteins loaded on the gel. Note that LbM and LbM/N have identical spectra, whereas LbP/N is being converted to green derivatives, with a Soret band of lower intensity and a hypsochromic shift of the 625-nm charge transfer absorption band. (*C*) Mass spectra of the hemes from Lb*a* reconstituted with protoheme or mesoheme and then nitrated. Note the absence of nitration (*m/z* 620) in the mesoheme. Experiments shown in *A* and *B* were repeated three times and the experiment shown in *C* was repeated twice, each with a different apoLb preparation, producing identical results.

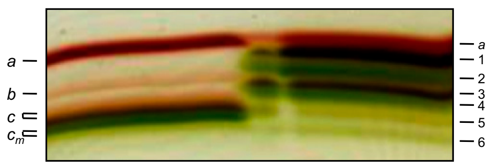

Fig. 2. Nitration of Lb*a* and separation of the nitrated products on preparative IEF gels. (*Left*) Mixture of Lb*a*, Lb*b*, Lbc, and Lbc$_m$ standards. The two Lbc protein bands correspond to Lbc$_1$ and Lbc$_2$+c$_3$. (*Right*) Lba (500 μM) purified from soybean nodules was nitrated with $NaNO_2$ (500 mM) for 48 h in citrate buffer (pH 5.5), yielding six derivatives (Lb*a*N1 to Lb*a*N6). (*Center*) A similar pattern of Lb*a*N derivatives was obtained when nitration was performed in phosphate buffer (pH 7.0). These experiments were repeated at least twice with identical results.

because nitrous acid (HNO_2, pK_a= 3.2) can give rise to NO_2^+ (Fig. 3). We obtained similar results with Mb and Lb. Addition of 10 mM cyanide, a strong ligand of both hemoproteins, completely prevented nitration, indicating that the reaction involves the heme Fe. To examine whether $ONOO^-$ was the nitrating agent, we used 3-morpholinosydnonimine hydrochloride (SIN-1) because synthetic $ONOO^-$ is a very short-lived molecule in buffered solutions. Spontaneous decomposition of SIN-1 yields NO• and superoxide anion radicals (O_2^-•), which react with each other to form $ONOO^-$, and thus SIN-1 can mimic a slow exposure of the protein to $ONOO^-$ (Fig. 3). Incubation of Mb or Lb*a* with 0.5–1 mM SIN-1 at pH 5.5 or 7.0 for up to 4 h did not nitrate the heme, excluding any contribution of free $ONOO^-$ to nitration. Likewise, an exogenous supply of superoxide dismutase (50–100 μg) or catalase (50–100 μg) did not prevent nitration, and therefore production of O_2^-• radicals or H_2O_2 outside the protein is not involved in the reaction. Addition of 30–100 μM H_2O_2 did not promote nitration, confirming that peroxide is apparently not required. In contrast, incubation of

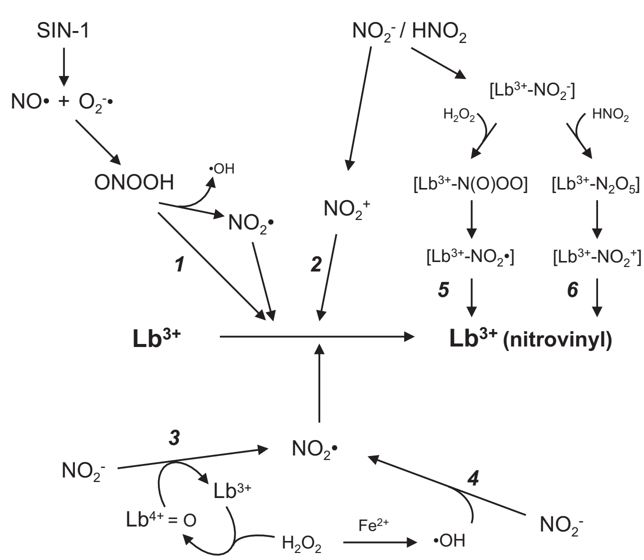

Fig. 3. Mechanisms that may be operative in the nitration of Tyr residues and heme groups of hemoproteins. The pathways have been exemplified for Lb but are also extensive to Mb and Hb. Some intermediates are indicated in square brackets only to mean that they are formed inside the heme pocket but, except for the nitrite and peroxynitrite complexes, are not necessarily bound to the heme. Experiments designed to test these pathways are described in the text. Additional abbreviations: Lb^{3+}, ferric Lb; Lb^{4+}=O, ferryl Lb; Lb^{3+}(nitrovinyl), ferric Lb bearing a vinyl-bound NO_2 group in the heme.

Mb or Lb*a* with 1 mM desferrioxamine (DFO) for 2–48 h inhibited nitration substantially (Fig. S6). DFO is a natural Fe chelator commonly used to establish the dependence of biological reactions on free $Fe^{2+/3+}$ ions, but can also intercept free radicals (39). To gain information on the inhibitory effect of DFO and the role of metals on Lb*a* nitration, we used ferrioxamine (1 mM), prepared by equimolar mixing of DFO and Fe^{3+} ions, and two powerful metal chelators, diethylenetriamine pentaacetic acid (1 mM) and Chelex resin (5 mg). Neither FO (Fig. S6) nor the other two compounds had any effect on heme nitration when added to the hemoprotein before NO_2^-. Therefore, free-metal ions are not required for the reaction and DFO needs to have the hydroxamic moities unblocked to inhibit nitration, which is consistent with the high affinity binding of DFO for heme (40).

Discussion

Green pigments and nitrated derivatives have been generated in vitro from animal and plant hemoproteins. Thus, human and equine Mb can be nitrated in the heme and in the Tyr^{103} and Tyr^{146} residues, depending on the Mb source and on the relative concentrations of NO_2^- and H_2O_2 (33, 41). In the case of plant hemoproteins, HRP was found to be nitrated on the vinyl groups (42) and a green derivative of Lb has been produced by oxidative reaction with H_2O_2 (43). The latter authors surmised that the green Lb species was formed at least in part by heme-globin cross-linking. We failed to detect similar compounds in vivo but found instead that the green Lbs of soybean originated by nitration of the heme. Furthermore, spectroscopic and reconstitution analyses of the hemoprotein revealed that the NO_2 group is on the 4-vinyl (Fig. S1). The modified Lbs were reproducibly synthesized in vitro by exposing the proteins to excess NO_2^-. These findings are fully consistent with a recent study showing that nitration of HRP heme occurs preferentially on the 4-vinyl rather than on the 2-vinyl (42). Nevertheless, nitriMb and nitriHb are nitrated on the 2-vinyl (33–35), suggesting that multiple isomers can be formed during nitration and that the vinyl group that is preferentially nitrated may be predicted by its relative availability to nitration reagents within the heme pocket. The regiospecificity of Lb heme nitration is indeed consistent with the crystal structure of soybean Lb*a* (44), which shows a greater accessibility of the 4-vinyl relative to the 2-vinyl when considering both surface electrostatic charges and steric restrictions for insertion of a NO_2 group (Fig. 4). It also should be noted that the NMR spectra tell us that the Lb protein imposes strict binding of the unsymmetrical heme molecule in only one orientation at equilibrium. Thus, the specific placement of the 2- and 4-vinyl groups, as shown in Fig. 4, defines a strong thermodynamic preference for the observed heme orientation, which, along with the accessibility of the 4-vinyl group seen in the structure, dictates that only the 4-vinyl group is attacked. In an early study, however, three Lba_m derivatives were found to exhibit virtually identical Soret-visible spectra (23), and here we found also different Lba_m products from in vitro nitration of Lb*a*. In light of the present results, we propose that these products are isomers differing in the site of the NO_2 group on the 4-vinyl, such as the α- or β-carbons and/or *cis*- or *trans*-configuration (Fig. S1).

How was the nitrated heme produced? We used RNS scavengers and releasing compounds, antioxidants, and metal chelators to gain insights on the nature of nitrating molecules (Fig. 3 and Fig. S6). Nitration of Mb and Lb requires binding of NO_2^- to the heme because it was inhibited by cyanide. The reaction is strongly pH-dependent, which points out the implication of a nitrating agent derived from HNO_2 rather than from NO_2^- itself. We can exclude a direct involvement of ONOOH formed outside the protein (pathway 1) because SIN-1 did not nitrate the Lb heme and superoxide dismutase and catalase did not prevent nitration. The same conclusion can be drawn for an oxidative

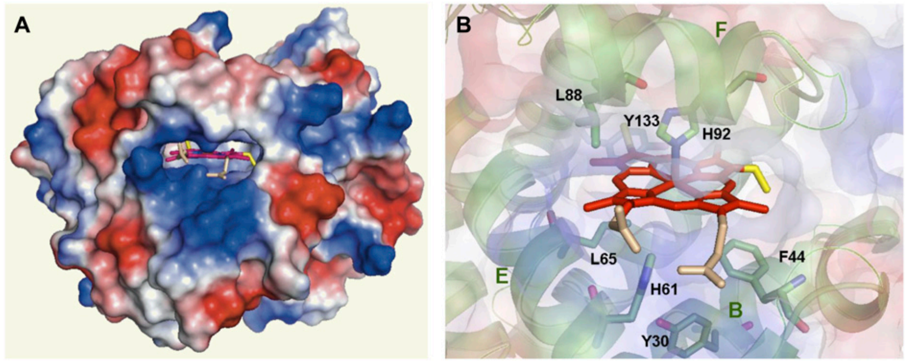

Fig. 4. Heme pocket of soybean Lb*a* [PDB accession 1BIN (44)] showing relevant α-helices and amino acid residues. (*A*) Electrostatic potential surface of the whole protein, showing heme localization. (*B*) Detail of the heme pocket. Ribbon diagram showing side-chains B, E, and F, with stick representation of the relevant amino acid residues, including proximal His[92] and distal His[61]. The vinyl groups of the heme are highlighted in yellow and the propionic groups in pink. Electrostatic potential surface is overlapped as transparency. Molecular structures were inspected, analyzed, and plotted with PyMol (56).

attack of NO_2^+, which may be formed outside the protein from HNO_2 decomposition (pathway 2), because addition of 1–10 mM nitronium tetrafluoroborate (NO_2BF_4) did not elicit heme nitration. Two alternative mechanisms, involving oxidation of NO_2^- to NO_2• by ferryl Lb (pathway 3) or by •OH generated via Fenton reactions (pathway 4), can be also discarded because nitration did not require H_2O_2 and was not dependent on free-metal ions. A mechanism of protein nitration based on Fenton chemistry with free metals or heme was initially proposed as an alternative to the $ONOO^-$ pathway (45). Exogenous H_2O_2 is not required either for the nitration of HRP heme (42) or for the production of NO_2-Tyr on a plant Hb (46). In these two cases, the nitrating agent is proposed to be the NO_2• radical based on the peroxidase activity (pathway 3) of the hemoproteins (42, 46). In fact, in these and our own studies, the possibility that H_2O_2 might be generated inside the heme pocket cannot be entirely ruled out. This possibility is unlikely, however, because addition of up to 100 μM H_2O_2 did not accelerate nitration. Recently, two additional mechanisms have been proposed for nitration of Mb (38, 41) and Hb (34) with a large excess of NO_2^-. As in our case, these two pathways require binding of NO_2^- to the heme. The first one (pathway 5) entails a subsequent reaction of the [heme-NO_2^-] complex with H_2O_2 to form a heme-bound peroxynitrite [heme-N(O)OO] species (38, 41). The nitration potential of this pathway for Lb could nevertheless be markedly diminished, as ferric Lb isomerizes $ONOO^-$ to NO_3^- at rates that are 10-fold higher than those for Mb or Hb (47). This pathway would require formation of H_2O_2 inside the heme crevice and probably decomposition of the protonated species [heme-N(O)OOH] to NO_2• radical. The second one (pathway 6) proposes that N_2O_5 is an intermediate (34). In this case, the [heme-NO_2^-] complex would react with another molecule of HNO_2, giving rise to N_2O_5, which in turn would decompose to NO_2^+ and NO_3^-. Our findings that HNO_2 is the precursor of the nitrating agent and that a [heme-NO_2^-] complex is a prerequisite for nitration are fully consistent with this hypothesis. Specifically, we propose that nitration is mainly a result of an electrophilic attack on the vinyl by the NO_2^+ generated from HNO_2 inside the heme pocket according to pathway 6, although we cannot discard the simultaneous formation of NO_2• radical by pathway 5, as mentioned earlier.

The deoxyferrous and oxyferrous forms of Lb are predominant in nodules, but other heme oxidation states and Lb complexes are also present. These include ferric Lb and the ferrous Lb-NO• (nitrosyl) complex that have been detected in intact nodules (48, 49). Ferric Lb can arise from several oxidative reactions, including the autoxidation of oxyferrous Lb or the reaction of NO• with oxyferrous Lb (47). In nodules, NO_2^- and NO• are mainly produced as a result of the nitrate reductase activities in the cytosol and bacteroids (50–52). Under natural conditions, nitration reactions are likely to occur because Lb may be exposed to NO_2^- over weeks or months and because the pH decreases to 5.5 during nodule senescence (53). The identification of Lbs bearing a nitrovinyl in their hemes provides conclusive evidence that nitrating and oxidizing RNS are produced in nodules. These reactive molecules are increasingly produced during aging or stressful conditions, in accord with the enhanced concentrations of Lba_m and Lbc_m observed in senescing nodules (24). Because these green proteins appear not to be competent for O_2 transport (23, 24), it will be of interest to determine whether they are unavoidable by-products of Lb-mediated RNS detoxification or perform as yet unknown functions in legume nodules.

Materials and Methods

Biological Material. Soybean plants (*Glycine max* cvs Hobbit or Williams × *Bradyrhizobium japonicum* strains 61A89 or USDA110) were grown under environment controlled conditions until the late vegetative growth stage (22). Nodules were harvested in liquid nitrogen and stored at −80 °C.

Purification of Lbs, Protein Identification, and Molecular Mass Determination. Soybean Lbs were purified using ammonium sulfate precipitation and chromatographic steps in hydroxylapatite, Sephadex G-75, and DE-52 columns (22, 23). Proteins were subjected to in-gel digestion with trypsin using a Digest MSPro (Intavis). Peptide and protein identification was performed by peptide mass fingerprinting in a MALDI-TOF instrument (Applied Biosystems) as previously described (54). The molecular masses of Lbs were determined by MALDI-TOF/MS. Details of all these procedures are provided in *SI Materials and Methods*.

Structural Analyses of Hemes and Hemoproteins. Details of equipment and protocols used for MS, NMR, and RR analyses are given in *SI Materials and Methods*.

Production of Recombinant Soybean Lb*a*. Recombinant Lb*a* was used instead of protein purified from soybean nodules to duplicate nitration experiments, producing identical results. The recombinant protein was expressed using conventional protocols described in *SI Materials and Methods.*

Reconstitution and in Vitro Nitration of Hemoproteins. The apoproteins of Mb and Lb*a* were obtained by the acid-butanone method (55). After neutralization of the aqueous phase with phosphate buffer (pH 7.0), the apoproteins were incubated overnight with a twofold excess of protoheme or mesoheme, dialyzed, and nitrated. For time-course studies of nitration, hemoproteins (150–200 μM) were treated with $NaNO_2$ (200 mM) in 50 mM phosphate buffer (pH 5.5 or 7.0) for 2–48 h at room temperature. The mixtures were dialyzed, concentrated, and resuspended in water (IEF analysis) or in 10 mM NH_4HCO_3 (MS analysis).

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1. Vinogradov SN, et al. (2005) Three globin lineages belonging to two structural classes in genomes from the three kingdoms of life. *Proc Natl Acad Sci USA* 102:11385–11389.
2. Gardner PR (2005) Nitric oxide dioxygenase function and mechanism of flavohemoglobin, hemoglobin, myoglobin and their associated reductases. *J Inorg Biochem* 99:247–266.
3. Pesce A, et al. (2002) Neuroglobin and cytoglobin. Fresh blood for the vertebrate globin family. *EMBO Rep* 3:1146–1151.
4. Appleby CA, Bergersen FJ (1980) *Methods for Evaluating Biological Nitrogen Fixation*, ed Bergersen FJ (John Wiley, Chichester), pp 315–335.
5. Igamberdiev AU, Hill RD (2004) Nitrate, NO and haemoglobin in plant adaptation to hypoxia: An alternative to classic fermentation pathways. *J Exp Bot* 55:2473–2482.
6. Perazzolli M, Romero-Puertas MC, Delledonne M (2006) Modulation of nitric oxide bioactivity by plant haemoglobins. *J Exp Bot* 57:479–488.
7. Sturms R, DiSpirito AA, Hargrove MS (2011) Plant and cyanobacterial hemoglobins reduce nitrite to nitric oxide under anoxic conditions. *Biochemistry* 50:3873–3878.
8. Trevaskis B, et al. (1997) Two hemoglobin genes in *Arabidopsis thaliana*: The evolutionary origins of leghemoglobins. *Proc Natl Acad Sci USA* 94:12230–12234.
9. Bustos-Sanmamed P, et al. (2011) Regulation of nonsymbiotic and truncated hemoglobin genes of *Lotus japonicus* in plant organs and in response to nitric oxide and hormones. *New Phytol* 189:765–776.
10. Becana M, Klucas RV (1992) Oxidation and reduction of leghemoglobin in root nodules of leguminous plants. *Plant Physiol* 98:1217–1221.
11. Fuchsman WH, Appleby CA (1979) Separation and determination of the relative concentrations of the homogeneous components of soybean leghemoglobin by isoelectric focusing. *Biochim Biophys Acta* 579:314–324.
12. Whittaker RG, Moss BA, Appleby CA (1979) Determination of the blocked N-terminal of soybean leghemoglobin *b*. *Biochem Biophys Res Commun* 89:552–558.
13. Marcker A, Lund M, Jensen EØ, Marcker KA (1984) Transcription of the soybean leghemoglobin genes during nodule development. *EMBO J* 3:1691–1695.
14. O'Brian MR (1996) Heme synthesis in the *rhizobium*-legume symbiosis: A palette for bacterial and eukaryotic pigments. *J Bacteriol* 178:2471–2478.
15. Brown SB, Houghton JD, Wilks A (1990) Heme degradation and biosynthesis of bilins. *Biosynthesis of Heme and Chlorophylls*, ed Dailey HA (McGraw-Hill, New York), pp 543–575.
16. Baudouin E, Frendo P, Le Gleuher M, Puppo A (2004) A *Medicago sativa* haem oxygenase gene is preferentially expressed in root nodules. *J Exp Bot* 55:43–47.
17. Virtanen AI, Laine T (1946) Red, brown and green pigments in leguminous root nodules. *Nature* 157:25–26.
18. Lehtovaara P, Perttilä U (1978) Bile-pigment formation from different leghaemoglobins. Methine-bridge specificity of coupled oxidation. *Biochem J* 176:359–364.
19. Roponen I (1970) The effect of darkness on the leghemoglobin content and amino acid levels in the root nodules of pea plants. *Physiol Plant* 23:452–460.
20. Puppo A, et al. (2005) Legume nodule senescence: Roles for redox and hormone signalling in the orchestration of the natural aging process. *New Phytol* 165:683–701.
21. Becana M, Matamoros MA, Udvardi M, Dalton DA (2010) Recent insights into antioxidant defenses of legume root nodules. *New Phytol* 188:960–976.
22. Jun H-K, Sarath G, Wagner FW (1994) Detection and purification of modified leghemoglobins from soybean root nodules. *Plant Sci* 100:31–40.
23. Jun H-K, et al. (1994) Characteristics of modified leghemoglobins isolated from soybean (*Glycine max* Merr.) root nodules. *Plant Physiol* 104:1231–1236.
24. Wagner FW, Sarath G (1987) *Plant Senescence: Its Biochemistry and Physiology*, eds Thomson WW, Nothnagel EA, Huffaker RC (Am Soc Plant Physiologists, Rockville), pp 190–197.
25. Lehtovaara P, Ellfolk N (1975) Purification and properties of *Phaseolus vulgaris* leghemoglobin (PhLb). *Acta Chem Scand B* 29:56–60.
26. Trewhella J, Wright PE (1980) ^{1}H-NMR studies of ferric soybean leghemoglobin: Assignment of hyperfine shifted resonances of complexes with cyanide, nicotinate, pyridine and azide. *Biochim Biophys Acta* 625:202–220.
27. Mabbutt BC, Wright PE (1983) ^{1}H NMR studies of complexes of ferric leghemoglobin with substituted pyridines and nicotinic acids. *J Inorg Biochem* 18:123–132.
28. Shokhireva TK, Shokhirev NV, Berry RE, Zhang H, Walker FA (2008) Assignment of the ferriheme resonances of high- and low-spin forms of the symmetrical hemin-reconstituted nitrophorins 1-4 by ^{1}H and ^{13}C NMR spectroscopy: The dynamics of heme ruffling deformations. *J Biol Inorg Chem* 13:941–959.
29. Desbois A, Mazza G, Stetzkowski F, Lutz M (1984) Resonance Raman spectroscopy of protoheme-protein interactions in oxygen-carrying hemoproteins and in peroxidases. *Biochim Biophys Acta* 785:161–176.
30. Lin-Vien D, Colthup NB, Fateley WG, Grasselli JG (1991) *The Handbook of Infrared and Raman Characteristic Frequencies of Organic Molecules* (Academic Press, San Diego), pp 179–190.
31. Hu S, Smith KM, Spiro TG (1996) Assignment of protoheme resonance Raman spectrum by heme labeling in myoglobin. *J Am Chem Soc* 118:12638–12646.
32. Picaud T, Le Moigne C, Loock B, Momenteau M, Desbois A (2003) Nonplanar distortions of bis-base low-spin iron(II)-porphyrinates: Absorption and resonance Raman investigations of cross-trans-linked iron(II)-basket-handle porphyrin complexes. *J Am Chem Soc* 125:11616–11625.
33. Bondoc LL, Timkovich R (1989) Structural characterization of nitrimyoglobin. *J Biol Chem* 264:6134–6145.
34. Otsuka M, et al. (2010) Covalent modifications of hemoglobin by nitrite anion: Formation kinetics and properties of nitrihemoglobin. *Chem Res Toxicol* 23:1786–1795.
35. Yi J, Thomas LM, Musayev FN, Safo MK, Richter-Addo GB (2011) Crystallographic trapping of heme loss intermediates during the nitrite-induced degradation of human hemoglobin. *Biochemistry* 50:8323–8332.
36. Olah GA, Narang SC, Olah JA, Lammertsma K (1982) Recent aspects of nitration: New preparative methods and mechanistic studies (a review). *Proc Natl Acad Sci USA* 79:4487–4494.
37. Brennan ML, et al. (2002) A tale of two controversies: Defining both the role of peroxidases in nitrotyrosine formation in vivo using eosinophil peroxidase and myeloperoxidase-deficient mice, and the nature of peroxidase-generated reactive nitrogen species. *J Biol Chem* 277:17415–17427.
38. Nicolis S, Monzani E, Roncone R, Gianelli L, Casella L (2004) Metmyoglobin-catalyzed exogenous and endogenous tyrosine nitration by nitrite and hydrogen peroxide. *Chemistry* 10:2281–2290.
39. Bartesaghi S, et al. (2004) Reactions of desferrioxamine with peroxynitrite-derived carbonate and nitrogen dioxide radicals. *Free Radic Biol Med* 36:471–483.
40. Baysal E, Monteiro HP, Sullivan SG, Stern A (1990) Desferrioxamine protects human red blood cells from hemin-induced hemolysis. *Free Radic Biol Med* 9:5–10.
41. Nicolis S, et al. (2006) Easy oxidation and nitration of human myoglobin by nitrite and hydrogen peroxide. *Chemistry* 12:749–757.
42. Wojciechowski G, de Montellano PR (2007) Radical energies and the regiochemistry of addition to heme groups. Methylperoxy and nitrite radical additions to the heme of horseradish peroxidase. *J Am Chem Soc* 129:1663–1672.
43. Moreau S, Davies MJ, Puppo A (1995) Reaction of ferric leghemoglobin with H_2O_2: Formation of heme-protein cross-links and dimeric species. *Biochim Biophys Acta* 1251:17–22.
44. Hargrove MS, et al. (1997) Characterization of recombinant soybean leghemoglobin a and apolar distal histidine mutants. *J Mol Biol* 266:1032–1042.
45. Thomas DD, Espey MG, Vitek MP, Miranda KM, Wink DA (2002) Protein nitration is mediated by heme and free metals through Fenton-type chemistry: An alternative to the NO/O_2^- reaction. *Proc Natl Acad Sci USA* 99:12691–12696.
46. Sakamoto A, et al. (2004) Three distinct *Arabidopsis* hemoglobins exhibit peroxidase-like activity and differentially mediate nitrite-dependent protein nitration. *FEBS Lett* 572:27–32.
47. Herold S, Puppo A (2005) Oxyleghemoglobin scavenges nitrogen monoxide and peroxynitrite: A possible role in functioning nodules? *J Biol Inorg Chem* 10:935–945.
48. Lee KK, Shearman LL, Erickson BK, Klucas RV (1995) Ferric leghemoglobin in plant-attached leguminous nodules. *Plant Physiol* 109:261–267.
49. Mathieu C, Moreau S, Frendo P, Puppo A, Davies MJ (1998) Direct detection of radicals in intact soybean nodules: Presence of nitric oxide-leghemoglobin complexes. *Free Radic Biol Med* 24:1242–1249.
50. Becana M, Minchin FR, Sprent JI (1989) Short-term inhibition of legume N_2 fixation by nitrate. I. Nitrate effects on nitrate-reductase activities of bacteroids and nodule cytosol. *Planta* 180:40–45.
51. Meakin GE, et al. (2007) The contribution of bacteroidal nitrate and nitrite reduction to the formation of nitrosylleghaemoglobin complexes in soybean root nodules. *Microbiology* 153:411–419.
52. Horchani F, et al. (2011) Both plant and bacterial nitrate reductases contribute to nitric oxide production in *Medicago truncatula* nitrogen-fixing nodules. *Plant Physiol* 155:1023–1036.
53. Pladys D, Barthe P, Rigaud J (1988) Changes in intracellular pH in French-bean nodules induced by senescence and nitrate treatment. *Plant Sci* 56:99–106.
54. Casanovas A, Carrascal M, Abián J, López-Tejero MD, Llobera M (2009) Discovery of lipoprotein lipase pI isoforms and contributions to their characterization. *J Proteomics* 72:1031–1039.
55. Ascoli F, Fanelli MR, Antonini E (1981) Preparation and properties of apohemoglobin and reconstituted hemoglobins. *Methods Enzymol* 76:72–87.
56. DeLano WL (2002) *The PyMol User's Manual* (DeLano Scientific, Palo Alto, CA).