Transcription of Nuclear Organellar DNA in a Model Plant System

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Abstract

Endosymbiotic gene transfer from cytoplasmic organelles (chloroplasts and mitochondria) to the nucleus is an ongoing process in land plants. Although the frequency of organelle DNA migration is high, functional gene transfer is rare because a nuclear promoter is thought necessary for activity in the nucleus. Here we show that a chloroplast promoter, 16S rrn, drives nuclear transcription, suggesting that a transferred organellar gene may become active without obtaining a nuclear promoter. Examining the chromatin status of a known de novo chloroplast integrant indicates that plastid DNA inserts into open chromatin and that this relaxed condition is maintained after integration. Transcription of nuclear organelle DNA integrants was explored at the whole genome level by analyzing RNA-seq data of Oryza sativa subsp. japonica, and utilizing sequence polymorphisms to unequivocally discriminate nuclear organelle DNA transcripts from those of bona fide cytoplasmic organelle DNA. Nuclear copies of organelle DNA that are transcribed show a spectrum of transcriptional activity but at comparatively low levels compared with the majority of other nuclear genes.

Key words: endosymbiotic gene transfer, nuclear integrants of organellar DNA, open chromatin.

Introduction

The transfer of prokaryotic DNA molecules into the nuclear genome that has occurred during two bacterial endosymbioses has played a major part in eukaryote evolution. Many endosymbiont genes were captured and activated by the nucleus and transferred DNA also contributed in more complex ways to the heterogeneity of the nuclear gene complement (Timmis et al. 2004). This endosymbiotic gene transfer (EGT) also resulted in massive functional relocation to the nucleus of genes that were formerly located in the endosymbionts (Gray et al. 1999; Timmis et al. 2004; Bock and Timmis 2008), explaining the much reduced size of extant mitochondrial and chloroplast genomes compared with their prokaryotic ancestors. Various steps in EGT have been recapitulated experimentally in yeast (Thorsness and Fox 1990), and in Nicotiana tabacum where the frequency of the first step—DNA transfer per se—was found to be surprisingly high (Huang et al. 2003; Stegemann et al. 2003; Wang, Lloyd, et al. 2012). However, for the successful relocation of functional organellar genes, mere insertion of DNA into the nuclear genome is not sufficient because of major differences in control of gene expression between the nucleus and the prokaryotic endosymbionts. For this reason, functional activation of plastid-derived genes in the nucleus is much rarer. However, despite its rarity, the process has been demonstrated experimentally by two independent research teams (Stegemann and Bock 2006; Lloyd and Timmis 2011) to involve the acquisition of nuclear transcription and polyadenylation motifs. In a special case, the chloroplast psbA promoter has been reported to be weakly active in the nucleus without any modification (Cornelissen and Vandewiele 1989), and nuclear insertion of multiple copies of a spectinomycin resistance gene, aadA, driven by this promoter leads immediately to selectable spectinomycin resistance (Lloyd and Timmis 2011).

Cytoplasmic organellar DNAs integrate into the nuclear genome through nonhomologous end joining (NHEJ) (Richetti et al. 1999; Lloyd and Timmis 2011; Wang, Lloyd, et al. 2012), and they insert preferentially into open chromatin regions (Wang and Timmis 2013). Likewise, recent human nuclear integrants of mitochondrial DNAs (numts) are commonly located in, or closely adjacent to, regions of open chromatin (Tsuiji et al. 2012). Open chromatin regions are often
depleted in nucleosome, a circumstance that permits greater access to interacting molecules (Hogan et al. 2006; Kim et al. 2007; Song et al. 2011), including the machinery of NHEJ and of transcription. Thus, although activity of the psbA in the nucleus may be explained by fortuitous nuclear transcription motifs (Lloyd and Timmis 2011), the likelihood exists of low level transcription of nuclear integrants of organellar DNA (norgs) simply because they tend to occupy open chromatin. Taking these observations together, we hypothesized that the majority of inserted organellar DNA may be transcribed directly after migration to the nucleus without the necessity to acquire nuclear transcription motifs, though the resulting mRNAs may lack the signals required for translation.

Here, we show that a 16S rm plastid promoter-driven reporter gene located in a de novo experimental chloroplast DNA integrant is transcribed after nuclear transfer, indicating that 16S rm promoter can be immediately active in nucleus, though it appears to contain none of the cryptic nuclear signals that appeared to explain the activity of the psbA promoter. We investigated the chromatin status of a fully transcribed immediately after nuclear transfer, indicating that plastid DNA integrant might be transcribed immediately without acquiring a nuclear promoter. To further explore the transcription of norgs at the whole genome level, RNA-seq data of Oryza sativa subsp. japonica were analyzed by searching for polymorphic RNAs containing single nucleotide differences (SNPs) and indels which unequivocally distinguish norg transcripts from those of bona fide cytoplasmic organelle DNA. A set of norg-specific transcripts was identified in this way, and their transcriptional patterns showed a continuous distribution similar to that of other nuclear genes. However their average level of RNA abundance was much lower, suggesting that plastid promoters work weakly in the nucleus or that the norgs were nonspecifically transcribed because they were located in open chromatin. Some norgs with the highest transcriptional characteristics within the range of active nuclear genes were further investigated, and most were found to be inserted into a nuclear gene.

Results

Transcription of a Plastid Promoter-Driven Reporter Gene in the Nucleus

Because of the high sequence similarity between nuclear integrants of plastid DNAs (nupts) and their plastid counterparts, it is difficult to demonstrate their transcription unequivocally. However, the gs1.2 tobacco line (Sheppard et al. 2008) allowed us to determine whether a plastid promoter other than psbA is active in the nucleus. The gs1.2 line contains a de novo experimental chloroplast integrant harboring two copies of a 16S rm promoter-driven aadA gene in figure 1A. Transcripts of aadA were demonstrated by reverse transcription (RT)-PCR demonstrating activity in the nucleus (fig. 1B) using aadA driven by the psbA promoter in the tobacco line kr2.2 (Lloyd and Timmis 2011), as a positive control. The greater transcript accumulation of aadA in gs1.2 (fig. 1B) is consistent with two copies of the reporter gene in gs1.2 compared with a single copy in kr2.2 (fig. 1A). These results suggest that the 16S rm and the psbA promoters are equally able to function directly in the nucleus. No cryptic nuclear transcription motifs such as TATA and CAAT are seen in 16S rm promoter (Sheppard et al. 2008). Therefore, it seems likely that transcriptional activity is facilitated by the nupts occupying open chromatin regions of the nucleus rather than the fortuitous presence of euakaryotic sequence motifs that were previously held responsible for promoter activity in the case of aadA.

Fig. 1.—Determination of aadA gene copy number and transcript accumulation. (A) The comparative copy number of aadA in gs1.2 by real-time quantitative PCR. Both kr2.2 and gs1.2 are experimental gene-transfer lines of Nicotiana tabacum. The control (kr2.2) contains a single copy of aadA (Lloyd and Timmis 2011). (B) RT-PCR analysis of plastid promoter-driven aadA genes in the nucleus. Transcript accumulation of aadA genes driven by the psbA promoter (kr2.2) and the 16S rm (gs1.2) promoter is shown. Control RT-PCR using primers specific for RPL25 is also shown. Lanes marked “+” and “−” indicate samples with and without reverse transcriptase.
Chromatin Status within a De Novo Chloroplast DNA Integrant

Transcriptional activity is characteristic of open chromatin regions (Song et al. 2011), and recently formed human numts have been shown to favor open chromatin or regions flanking open chromatin (Tsuji et al. 2012). Therefore, the chromatin status of a fully characterized chloroplast DNA integrant in kr2.2 (Lloyd and Timmis 2011) and its preinsertion site in wild type (WT) seedlings was examined by DNase I-PCR. DNase I sensitivity is commonly used to interrogate DNA chromatin compaction.

In WT tobacco, chromatin at the site of integration of the de novo nupt in kr2.2 was found to be less compacted compared with a control heterochromatic region (fig. 2A). This supports previous findings (Wang and Timmis 2013) that cytoplasmic organellar DNA inserts preferentially into open chromatin. After insertion of approximately 17 kb (Lloyd and Timmis 2011) of chloroplast DNA in kr2.2 (fig. 2B), this region of chromatin remained uncompacted over its entire length (fig. 2). The 17-kb integrant containing two reporter genes was examined with three different primer pairs. In particular, chromatin containing the DNA segment harboring the neo and psbA promoters of the reporter genes was more accessible (fig. 2C, middle section) than regions close to the insertion site (fig. 2C, left and right sections), suggesting that both aadA and neo genes are transcriptionally active in the nucleus.

Although the neo gene, driven by the 35S promoter, is known to be highly active as it was used to detect the chloroplast DNA transfer event, aadA is driven by the chloroplast-specific psbA promoter which is expected to be much less active in the nucleus. It is possible that the undisturbed relaxed state of the chromatin is maintained because of the presence of the highly active 35S promoter driving neo or it may be that many norgs insert with minimal impact on neighboring genes.

Transcription of norgs in Oryza sativa subsp. japonica

The results in figure 18 confirm that some native chloroplast genes may be transcribed without modification after transfer to nucleus, in rare cases where they contain fortuitous eukaryotic promoters and, much more often, because they tend to integrate into active chromatin.

To investigate the generalized transcription of naturally occurring norgs, 3,032 numts and 1,417 nupts were identified in O. sativa subsp. japonica, and RNA-seq data (Zhang et al. 2012) searched for unambiguous matches. Base substitutions and indels located in norgs were utilized to distinguish unequivocal transcripts of norgs among total transcripts. These mutations were designated as checking points in norgs (CPINs) (fig. 3A), and only reads mapped with CPINs were retained for further analysis. A total of 90,413 CPINs were identified from 3,674 norgs. Most, often short, norgs were found to harbor one or two differences compared with their organellar counterparts, whereas longer ones regularly showed proportionately more CPINs (Spearman’s correlation, $r = 0.581544$, $P$ value < 2.2e-16). This necessarily
means that there are a large number of norgs with a minimal number of CPINs but sufficient polymorphisms were identified to permit a comprehensive and secure description of the transcription of norgs at the whole genome level.

After mapping the reads from eight RNA-seq samples to the genome of subsp. japonica, about 23% (21,156 out of 90,413) CPINs were found with matching reads in at least one sample. Of the 21,156 CPINs with matching reads, approximately 52% (11,125 out of 21,156) were found in only one RNA-seq sample, but around 8% (1,764 out of 21,156) were covered by reads in all eight available RNA-seq samples from seedling and callus (Zhang et al. 2012).

Next, we compared the transcription pattern between annotated genes and norgs in the eight RNA samples. The profiles of all the norgs presented a continuous pattern similar to the annotated genes, but their average transcript abundance was lower (~3.7 reads per norg compared with ~6.6 reads per gene) (fig. 4). This is consistent with the observation that plastid promoters work more weakly in the nucleus than the majority of eukaryotic promoters (Lloyd and Timmis 2011).

Interestingly, approximately 0.4% of norgs were identified whose transcript abundance was equal to, or greater than, ten mapped read counts (fig. 4), which represents transcription well within the normal range of nuclear gene expression. This subset of characterized loci with higher levels of transcriptional activity was extracted for further analysis. Using the method described in the legend to figure 4, 17 norgs were found to be preferentially transcribed in seedling tissues and 12 in callus, with six of these identified in both tissue types (table 1). Fifteen of these norgs overlapped with, or were embedded within, annotated nuclear genes. This finding explains why this subset of norgs shows transcript accumulation levels that are comparable with known active nuclear genes and suggests that they represent an integral part of the associated gene transcripts (supplementary fig. S1, Supplementary Material online). The identification of 35 transcriptionally active norgs provides an evolutionary context for the previous finding that norgs can create new functional exons in the nuclear genome (Noutsos et al. 2007), though none of the genes described by Noutsos et al. (2007) appeared in our analysis, probably because we examined only genes that showed at least ten reads per CPIN.

In order to determine whether organellar promoters function directly in the nucleus, the available 35 norg sequences were examined for organelle-type promoters. If promoter motifs were identified within 1 kb of upstream flanking DNA of the chloroplast or mitochondrial gene, the norg was classified as holding an organellar promoter. Overall, norgs with
FIG. 4.—Plots of norg activity with respect to other nuclear genes. Transcription of annotated nuclear genes and norgs is shown in the top and bottom panels, respectively. The transcription for each annotated gene was normalized as follows: The midbase for each exon of subsp. japonica annotated gene was chosen, and then short reads uniquely mapped to the midbase without mismatches were counted to assess the transcription of each exon. Finally, transcription of the annotated gene was normalized using the mean transcription of all exons. Each dot shows the transcription level (number of mapped reads in the coordinate axes) of nuclear genes (top) or norgs (bottom).

Table 1
Information of Transcribed norgs

<table>
<thead>
<tr>
<th>Tissue</th>
<th>No. of norgs</th>
<th>Overlapped or in Gene</th>
<th>Location in Gene</th>
<th>Flanked DH Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seedling</td>
<td>17</td>
<td>3</td>
<td>1 is exon; 2 are 3’-UTRs</td>
<td>9</td>
</tr>
<tr>
<td>Callus</td>
<td>12</td>
<td>8</td>
<td>8 are exons</td>
<td>4</td>
</tr>
<tr>
<td>Both</td>
<td>6</td>
<td>4</td>
<td>3 are exons; 1 is 3’-UTR</td>
<td>2 (seedling) 4 (callus)</td>
</tr>
</tbody>
</table>

Note.—UTR, untranslated region.
promoters identified in this way showed more transcripts than those that did not, but this difference was not statistically significant. More detailed analysis revealed a complex picture. Fifteen norgs (11 nupts and 4 numts) were found to harbor organellar promoters, whereas 20 (4 nupts and 16 numts) lacked promoters (fig. 5). Transcript levels of numts with promoters were significantly lower than the ones without promoters (Welch two sample t-test, $P = 5.485 \times 10^{-8}$) in seedling RNA, but there was an opposite trend in callus ($P = 0.009571$). The transcriptional level of nupts containing promoters was significantly higher than those without promoters in callus tissue ($P = 3.718 \times 10^{-6}$), but this difference was not significant in seedling RNA ($P = 0.07715$). This result indicates that organellar promoters may be active in the nucleus and that organellar promoters exhibit different transcriptional activity in different plant tissues. As the number of norgs we studied here is very limited, further work is required to elucidate these complex patterns.

Next, we investigated the connection between highly expressed norgs and open chromatin status by crosschecking norgs and 1 kb of flanking DNA with DNase I hypersensitive (DH) sites (Zhang et al. 2012) in O. sativa subsp. japonica. In seedling tissues, 9 of the 17 cases examined were located in open chromatin regions and 4 norgs of 12 tested were seen in callus tissues (table 1). For norgs transcribed in both tissues, two of the six identified were located in open chromatin regions in seedling tissues and four in callus. Considering the possibility that a nuclear promoter was adjacent to the norg, 1-kb flanking DNA of these norgs in table 1 were compared with annotated rice promoter regions in PlantProm (Shahmuradov et al. 2003), and only one norg transcribed in seedling tissue was found to overlap with a promoter within 1 kb of its flanking DNA, but none was found in callus. Thus we conclude that certain rare norgs are transcribed because of fortuitous sequence motifs that occur in the mitochondrial or chloroplast genomes, but a larger number can achieve transcription by occupying a region of active open chromatin. However, the highest norg transcription levels are found after insertion into an existing nuclear gene.

**Discussion**

Acquiring a eukaryotic promoter was thought to be essential for functional organellar gene transfer, but recent research (Lloyd and Timmis 2011) showed that transfer of multiple copies of the chloroplast psbA promoter-driven reporter gene leads directly to successful expression in the nucleus. Here we describe that the 16S rm plastid promoter is, like that of psbA, active in nucleus. Both psbA and 16S rm promoters are transcribed in the chloroplast by the plastid-encoded RNA polymerase (Sriraman et al. 1998; Hayashi et al. 2003) and they are most likely to be transcribed by nuclear DNA-dependent RNA polymerase II after they migrate to nucleus, suggesting that simple gene transfer from plastid-to-nucleus is immediately sufficient for transcriptional activity for some plastid genes. However, the power of these plastid promoters is much lower than that of evolved nucleus-specific promoters, a trend that we have now confirmed by whole genome analysis of norg transcription patterns in O. sativa subsp. japonica seedling and callus. Nonetheless, nuclear gene-comparable transcription levels were found for a set of 35 norgs and further analysis showed that a large proportion (15) of these were inserted into known nuclear genes. This finding demonstrates that plastid and mitochondrial DNAs not only diversify the nuclear genome but also contribute significantly to the transcriptome in rice. Interestingly, the number of actively transcribed norgs is different between seedling and callus tissues. This tissue-specific transcription of norgs is not surprising, because transcript accumulation levels of the large numt in Arabidopsis thaliana can be significantly increased by heat treatment (Pecinka et al. 2010; Tittel-Elmer et al. 2010), suggesting that cytoplasmic organellar promoters are environmentally responsive although they are weak under normal conditions. In addition, norgs may be transcribed by RNA polymerases IV or V, the homologs of DNA-dependent RNA polymerase II, and involved in RNA-directed DNA methylation. It will be interesting to study whether norgs are involved in nuclear DNA modification.
Plastid DNA is reported to contribute regulatory elements to a mitochondrial gene in its 3'-UTR region (Wang, Rousseau-Gueutin, et al. 2012). The finding of some norgs located in the 3'-UTR of annotated nuclear genes (table 1) suggests that cytoplasmic organelar DNA may likewise donate gene regulatory elements in the nucleus, and this thought is also supported by that norgs coincide with DH sites which can signify regulatory elements.

Materials and Methods
Plant Materials and PCR Assay
Tobacco plants were grown in sterile jars on half MS medium as previously described (Wang, Lloyd, et al. 2012). DNA and RNA were prepared using a DNeasy Plant Mini Kit (Qiagen) and an RNeasy Plant Mini Kit (Qiagen), respectively, according to the manufacturer's instructions.

Real-time quantitative PCR was performed as described previously (Yang et al. 2005). Primers used for determining copy number of aadA gene were 5'-GACTACCTTGGTGTACCTGCCTTTC-3' and 5'-GCCGTCATACCTGAAGCTAGACAG-3'. For normalizing the total DNA contents used in quantitative PCR, RPL25 amplification after chloroplast DNA insertion in kr2.2 were 5'-AAAGGGTTGGTTGTCTCTCAATCTT-3' was used as an internal standard (Schmidt and Delaney 2010).

Preparation of cDNA used in standard RT-PCR was carried out according to previous description (Wang, Lloyd, et al. 2012). Amplification of aadA cDNA used primers 5'-AGTATCGACTCAACTATCAGAGG-3' and 5'-GACTACCTTGGTGATCTC-3' was a negative control was amplified with primers 5'-GGGGTTGGCCTGGTGGCAAT-3' for left section; 5'-GGGGTTGGCCTGGTGGCAAT-3' for middle section; 5'-GGGGTTGGCCTGGTGGCAAT-3' for right section.

Identification of O. sativa subsp. japonica norgs
The chloroplast, mitochondrial, and nuclear genome sequences and annotation data of O. sativa subsp. japonica were downloaded from TIGR database (Release 5). Nupts and numts present in the subsp. indica genome were identified by using local BLASTN (version 2.2.23) (Altschul et al. 1990) with the parameters previously described (Wang, Rousseau-Gueutin, et al. 2012).

RNA-seq and Open Chromatin Regions
To investigate the transcription pattern of norgs from O. sativa subsp. japonica at whole-genome level, we downloaded RNA-seq and open chromatin data generated by DNase-seq (Zhang et al. 2012). The original FASTQ sequence file of RNA-seq data was downloaded from National Center for Biotechnology Information Gene Expression Omnibus (accession numbers: GSE26610 and GSE26734) and mapped back to O. sativa subsp. japonica genome (TIGR release 5) with no mismatch allowed using GSNAP (Wu and Nacu 2010). Then uniquely identified short reads were filtered for further analyses. CPINs were identified by pairwise sequence alignment between the nuclear DNA and chloroplast/mitochondrial DNA with LASTZ (Harris 2007). Reads mapped to CPINs were counted to represent the transcripts of norgs. The expression of genes was calculated as following description: Reads mapped to middle-base of each exon were counted as the expression of this exon, and then the mean value of all exons’ expression was calculated as the expression of this gene. The read counting and overlap of genes and norgs were determined by R package “GenomicFeatures,” and plots were generated with R package “ggplot2” (Wickham 2009; R Development Core Team 2010; Lawrence et al. 2013).

To compare the transcriptional levels of norgs with or without potential organellar promoters, we checked the genomic coordinates of 35 transcribed norgs in the chloroplast or mitochondrial genome. If a norg contained sequences that were within 1-kb upstream of an organellar gene, it was classified as norg with a potential organellar promoter. The average number of reads mapped to CPINs of each norg was calculated to reveal the transcriptional level of each norg. The transcription level difference between norgs (nupts and numts) with and without potential organellar promoters was calculated and tested using a Welch two sample t-test.

A Perl script was written for determining whether any highly transcribed norg insertion colocalized with nuclear gene. Open chromatin status of individual norgs was checked as previously described (Wang and Timmis 2013). Annotated rice promoter regions were retrieved from PlantProm (Shahmuradov et al. 2003). The overlap between promoter regions and 1-kb flanking regions of selected norgs was checked using R package “GenomicFeatures.”

Supplementary Material
Supplementary figure S1 is available at Genome Biology and Evolution online (http://www.gbe.oxfordjournals.org/).
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