# abd-A Regulation by the iab-8 Noncoding RNA

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Author Summary

Although long, noncoding RNAs have been found in many organisms, it has been difficult to assign to them any molecular function. The homeotic gene clusters in the fruit fly, Drosophila melanogaster, contain many such noncoding RNAs. We have characterized one such noncoding RNA, a 92 kb transcription unit from within the bithorax complex. This transcript, called the iab-8 ncRNA, is made in the cells of the central nervous system in the eighth abdominal segment, along with the homeotic transcription factor Abdominal-B. Another homeotic transcription factor, abdominal-A, is repressed in these cells. It has generally been assumed that abdominal-A repression in these cells is mediated by the Abdominal-B protein. However, here we show that it is not Abdominal-B that represses abdominal-A, but the iab-8 ncRNA. This repression is accomplished by two redundant mechanisms; the iab-8 precursor produces a micro RNA, which targets the abdominal-A mRNA, and iab-8 transcription interferes with the abdominal-A promoter, which lies just downstream of the iab-8 ncRNA poly(A) site.

Results/Discussion

Repression of abd-A in the 8th abdominal segment

In wild type embryos, abd-A expression is detected in the epidermis and CNS of PS7 to PS12 but not in PS13 (Figure 1A). Abd-B is strongly expressed in PS13, and it was initially claimed that Abd-B represses abd-A in PS13 [17], just as abd-A represses Ubx and Ubx represses Antp [18]. This repression hierarchy can account for the dominance of posterior homeotic genes over anterior ones, often called “posterior prevalence” [19]. Indeed, embryos homozygous for Df(3R)C4, which removes Abd-B, show ABD-A expression throughout PS13 (Figure 1B). However, the Df(3R)C4 deficiency extends downstream of the ABD-B transcription unit, removing all of the iab-7 regulatory region and part of iab-7 (Figure 2). Surprisingly, embryos homozygous for an Abd-B null point mutation, Abd-BD16, show Abd-B derepression in PS13 of the epidermis, but not in the CNS (Figure 1C). Homozygotes for Abd-BD16, a deletion removing all of the Abd-B coding sequences (Figure 2), show the same ABD-A expression pattern (not shown). This unexpected repression of ABD-A in the CNS can be seen most dramatically in the Abd-BD114 mutation. Abd-BD114 deletes the promoter for the Abd-B “n” transcript [20], expressed from PS10 through PS13, but leaves the promoters for the “s” transcripts expressed in PS14. In the CNS of Abd-BD114 homozygotes, abd-A does not fill in the gap left by the absence of Abd-B in PS13 (Figure 1D). Clearly then, there must be some function deleted by Df(3R)C4 that is not affected by Abd-BD114 or more subtle Abd-B mutations. Our attention turned to the iab-8 ncRNA, which appeared to initiate in the iab-8 region deleted in Df(3R)C4.

Mapping the iab-8 ncRNA exons

The spliced product of the iab-8 ncRNA was initially uncovered by a fortuitous insertion of an exon-trap mobile element. This element, a derivative of the Minos mobile element, is called Hostile takeover [M( insisting upon HT)] [21]. An insertion was recovered in the iab-6 domain of the BX-C (“TA” target site bases 83,277 & 85,270), named M( insisting upon HT)] [21]. Short (Figure 2). Surprisingly, embryos homozygous for an iab-8 precursor produces a micro RNA, which targets the abdominal-A mRNA, and iab-8 transcription interferes with the abdominal-A promoter, which lies just downstream of the iab-8 ncRNA poly(A) site.

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transcripts [2,21]. Graveley et al. [2] also reported transcripts from adult males with most of the same exons, but an alternate start site, in the \textit{iab-6} region.

The promoter for the \textit{iab-8} RNA maps distal to the \textit{Fab-8} boundary, in the \textit{iab-8} regulatory region [22]. The \textit{iab-8} region should be under Polycomb Group repression in parasegments 1–12, which explains why the transcript is only expressed in PS13 and 14 [11]. Exons 1–7 appear to be evenly spaced across the abdominal region of the bithorax complex, with one in each of the \textit{iab cis-} regulatory domains. A comparison with the genomic sequences of various \textit{Drosophila} species suggests that the sequences of the exons are not more conserved than those of the introns. However, the existence of the exons does appear to be conserved, in that the splice junctions are among the most conserved features of the exons. This is illustrated in Figure 3A for exon 3, in the \textit{iab-6} region. The embryonic expression pattern is also conserved; expression is restricted to PS13 and 14 in \textit{D. pseudoobscura} and \textit{D. virilis}, as it is in \textit{D. melanogaster} (see Figure S2).

The spliced product of the \textit{iab-8} RNA is non-coding by traditional criteria, but the possibility of small peptides [23,24] cannot be ruled out. In particular, exon 8 includes a potential 9 amino acid peptide, with appropriate translation initiation and termination signals, and the coding potential for this peptide is well conserved in \textit{D. ananassae}, \textit{D. pseudoobscura} and \textit{D. willistoni} (Figure 3B), although it is not found in \textit{D. virilis} and more distantly related species.

\textbf{\textit{abd-A}} repression by the \textit{iab-8} RNA

There are many chromosome rearrangements, mostly from the collection of E. B. Lewis, which interrupt the \textit{iab-8} ncRNA transcription unit. These can be used to test whether truncated versions of the \textit{iab-8} RNA can repress \textit{abd-A}. Rearrangement

\begin{figure}
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\includegraphics[width=\textwidth]{figure2.png}
\caption{Map of the abdominal half of the bithorax complex. The horizontal bar indicates the DNA sequence map, numbered in kb according to Martin et al. [4] (Genbank U31961). Base #1 corresponds to base 12,809,162 on chromosome 3R in release 5.37 of the \textit{Drosophila} genome. The coordinates proceed distal to proximal on chromosome 3R, which is opposite in orientation to the whole genome numbering. The regulatory domains \textit{iab-2} through \textit{iab-8} are color coded; the domain borders are defined by deletion mutations (\textit{Fab8} [22]; \textit{Fab7}, [41]; \textit{Mcp}, [44]; \textit{iab-3/iab-4}, L. Sipos personal communication), or inferred from the binding sites of the CTCF factor [45]. Below the DNA bar are shown the splicing patterns of \textit{abd-A} and \textit{Abd-B} (in black), a cDNA derived from the \textit{Mi/Hto-WP/LNP} insertion (red), and the MIP06894 cDNA (green). At the bottom, the splicing pattern for the \textit{iab-8} ncRNA is shown in dark blue, with numbered exons, and alternate 5’ or 3’ extensions indicated with light blue lines. Mutant lesions are indicated above the DNA bar. The rearrangement breakpoints are color coded according to their phenotypes when heterozygous with the \textit{mfs5649} insertion.}
\end{figure}

\begin{figure}
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\includegraphics[width=\textwidth]{figure3.png}
\caption{Evolutionary conservation. A. A comparison of exon 3 and neighboring bases with the homologous regions from the genomes of three \textit{Drosophila} species. B. Potential nine amino acid peptide within exon 8 of the \textit{iab-8} ncRNA. The \textit{D. melanogaster} sequence is compared to that of \textit{D. ananassae}. The initial methionine codon is preceded by a perfect translation start consensus sequence [46], and there are two stop codons after the 9th amino acid. The three bases altered in \textit{D. ananassae} are highlighted in red; only one changes the predicted amino acid.}
\end{figure}
breaks that truncate the iab-8 RNA near its start site cause a dramatic derepression of abd-A in the CNS of the 8th abdominal segment, indistinguishable from that seen in Df(3R)C4 homozygotes (Figure 1). Rearrangements with this effect include iab-7(9A)3, iab-6(1)l, iab-3(3R)11, and iab-4(1)366 (Figure 2 & 4). The same spread of ABD-A into the CNS of PS13 is seen with the Fab-D deletion, which removes the iab-8 ncRNA promoter (Figure 2). Interestingly, embryos homozygous for chromosome breaks mapping closer to abd-A show a much more subtle derepression of abd-A. In iab-3(5022) homozygotes, for example, weak misexpression is limited to a few cells (Figure 4). Similar weak misexpression is seen in homozygotes of iab-4(3)115 and iab-4(5022) (Figure 2). Finally, embryos homozygous for the iab-3(5022) rearrangement show abd-A misexpression in only a very few CNS cells in the most anterior part of the 8th abdominal segment (Figure 4). This break lies downstream of the poly(A) addition site of the major iab-8 transcript, but upstream of the abd-A transcription start site.

The difference between the two classes of breakpoints seems to be the expression of miR-iab-8. The iab-4(186) break, maps just upstream (within 3 kb) of the miR-iab-8 coding region and shows complete loss of abd-A repression in PS13. In contrast, the iab-3(5022) break maps ~5 kb downstream of miR-iab-8 and shows only slight misexpression. Thus, one might guess that miR-iab-8 is responsible for most of the repression of abd-A, especially since the 3’ UTR of abd-A includes sequences homologous to the “seed” region of miR-iab-8 [12,13]. However, embryos homozygous for a deletion of miR-iab-8 (ΔmiR-iab-8) do not show a dramatic misexpression of ABD-A in the PS13 CNS [11]. A closer examination of these homozygous embryos does reveal a weak misexpression of abd-A in a small number of nuclei in anterior PS13 (Figure 4), but clearly not the strong and widespread misexpression of iab-4(186). Thus, it appears that miR-iab-8 does repress abd-A in the PS13 CNS, but there must be a second, redundant function of the iab-8 RNA to completely repress abd-A. UBX expression in embryos is apparently not affected by this second function; its expression pattern in iab-7SGA62 homozygous embryos is the same as that in miR-iab-8 deletion homozygotes (not shown).

Fertility function of the iab-8 ncRNA
A deletion of the miR-iab-8 causes sterility in both sexes [11]. Thus, we expected that any combination of alleles that failed to make the miR-iab-8 micro RNA would be sterile, including, for example, an iab-7 break (iab-7(9A)3 or iab-7(9A)366) heterozygous with ΔmiR-iab-8 [11]. There is an insertion of the “PZ” P element ~4.2 kb downstream of the iab-8 RNA start site, designated mfs(3)05649 (here called mfs5649; Figure 2). Homozygotes are sterile in both sexes, and the females show the same phenotype (blockage of the oviduct) as is seen in ΔmiR-iab-8 homozygotes [25]. We assume the mfs5649 insertion truncates the iab-8 RNA, since it fails to complement with ΔmiR-iab-8 for the sterility phenotype. The Fab-D4 deletion (derived from the mfs5649 P element; Figure 2; [22]) is also sterile as a homozygote or as a heterozygote with ΔmiR-iab-8.

We tested rearrangement breakpoints in the iab-2,3, and 4 regions, downstream of the miR-iab-8 template, for fertility when heterozygous with the mfs5649 P element. Surprisingly, many rearrangement breakpoints 3’ to the miR-iab-8 template have a female sterility phenotype when heterozygous with mfs5649 (Figure 2); males of these genotypes are fertile. These sterile females show a failure of mature oocytes to move through the oviduct, much like mfs5649 homozygotes or the ΔmiR-iab-8 homozygotes. It does not seem likely that breakpoints downstream of the miR-iab-8 template interfere with the proper processing of the micro RNA, because these same breakpoints are fertile when heterozygous to ΔmiR-iab-8. It is possible that the subtle misexpression of ABD-A in PS13 seen in iab-3 breaks is responsible for the female sterility, especially if the misexpression is more dramatic at later times in development. Not all breakpoints give this female sterility phenotype, and there is no apparent order to

![Figure 4. ABD-A expression in rearrangements truncating the iab-8 ncRNA.](doi:10.1371/journal.pgen.1002720.g004)
the fertile and sterile breakpoint alleles (Figure 2). Some of the rearrangements may fuse the iab-3 region with novel transcription units, restoring the repression of abd-A in the critical cells.

Mechanism of repression

The iab-8 ncRNA could make a product, such as another miRNA, that represses abd-A. Indeed, there is a secondary structure hairpin in exon 6 of the spliced transcript that could serve as a miRNA precursor. The iab-8 ncRNA could also code for tiny peptides, as noted above (Figure 3B). These possibilities prompted us to misexpress the iab-8 ncRNA spliced product. A cDNA cassette, representing the major splicing product (Figure 2) plus 236 bp of genomic DNA downstream of the poly(A) addition site, was cloned into the pUAST vector [26]. P element transgenes were recovered and crossed to flies expressing the yeast GAL4 activator in abdominal segments 3–8 (parasegments 8–13). However, embryos containing both the GALA activator and the UAS/iab-8 cDNA target showed no apparent reduction in the abd-A levels in the segments expressing GALA (not shown).

The cDNA misexpression experiment does not rule out a product made from an intron, such as an RNA component of a diffusible repressive complex, as alleged for non-coding RNAs in mammalian HOX complexes [27]. If the putative second repressor involves a diffusible molecule, it should be able to act on both chromosomes, even if it is only produced by one. The miR-iab-8 micro RNA should be diffusible in this way, and so to examine the second repression function, we needed to test genotypes lacking miR-iab-8. Specifically, heterozygotes were made with the ΔmiR-iab-8 deletion on one chromosome, and with a mutation truncating the iab-8 RNA upstream of the miRNA template (mfs5649, iab-7^SCG62, or iab-7^145) on the other chromosome. Such embryos make the iab-8 RNA from only one chromosome, and cannot make the micro RNA from either. As shown in Figure 5, these embryos showed strong abd-A misexpression in the CNS of PS13 (the 8th abdominal segment), suggesting that the iab-8 RNA can only repress the copy of abd-A on the chromosome from which it is transcribed. To control for a potential effect of haploinsufficiency of the iab-8 RNA, the ΔmiR-iab-8 deletion was also tested over DfP9, a deletion that removes the entire bithorax complex. These ΔmiR-iab-8/DfP9 embryos show no apparent misexpression of ABD-A in PS13. Thus, the second iab-8 RNA repressive function must act only in cis.

In a similar test, we employed a duplication for the proximal two thirds of the complex, Dp(3;2)D109, which extends into the iab-5 region (at ~110 kb) [28]. This duplication includes abd-A, but lacks the iab-8 RNA promoter. Embryos homozygous for the ΔmiR-iab-8 deletion but containing this duplication also show ABDA misexpression in the PS13 CNS (Figure S3). Thus, there are two mechanisms by which the iab-8 RNA represses abd-A, first, through production of the iab-8 miRNA (acting in trans), and second, a repressive function acting only in cis. The Supplementary Table S1 summarizes which genotypes supply which repressive functions.

The cis-repression of one transcription unit by another is often termed transcriptional interference. This term, however, encompasses several possible molecular mechanisms [29]. An example of a long, ncRNA involved in transcriptional cis-repression is the XIST RNA, involved in mammalian X chromosome inactivation [30] (A recent report suggests that the XIST RNA can also work in trans [31]). Nascent transcripts are involved in repression in RNAi silencing of heterochromatin is fission yeast [32] and in RNA-directed DNA methylation in Arabidopsis [33]. By analogy to these systems, the iab-8 RNA could recruit gene silencing machinery to the site of its transcription. The RNA sequences required for such recruitment might be mapped by examination of deletions in the BX-C. Ideally, the iab-8 mRNA should be removed to have a clear assay for the cis repressor. We have checked embryos homozygous for the Fab7^3D deletion (Figure 2), which covers the site of the iab-8 mRNA precursor; they still show abd-A repression in the posterior CNS. Likewise, a double deletion chromosome, with ΔmiR-iab-8 and Fab7^3, also retains the cis repression. The Fab7^3 deletion (Figure 2) was tested because it removes a Polycomb Response Element [34,35] which is coincident with exon 2 of the cDNA. Two other deletions have been examined which span the iab-4 through iab-7 regions, although both retain the iab-8 miRNA (iab-4,5,6^Fab3,5DV and iab-6,7^Fab7; Figure 2). In these, we looked for more subtle misexpression, such as that seen in iab-3 breaks (Figure 4), but no such misexpression was seen. This analysis does not yet cover the iab-2 and iab-3 regions, nor does it exclude the possibility of multiple redundant sequences throughout the transcription unit that could recruit repressive factors.

A more likely repression mechanism, perhaps, is that the RNA polymerase transcribing the iab-8 RNA somehow interferes with the abd-A promoter. Examples of this type of transcriptional interference come from budding yeast, where the GAL7 gene is repressed by the upstream GAL10 transcript [36], and the SER3 gene is repressed by the upstream, noncoding SRG1 transcript [37]. In these cases, the 3' ends of the upstream transcripts are close to the downstream promoters, suggesting repression by occlusion of the downstream promoters or their proximal enhancers. If the iab-8 RNA interferes with an abd-A enhancer, that enhancer must lie downstream of the iab-4^Fab7 breakpoint, since abd-A is totally derepressed in the PS13 CNS in embryos homozygous for this break (Figure 4). The abd-A promoter seems like the most likely target of interference, since the major poly(A) site of the iab-8 RNA lies only 1.1 kb upstream of the initiation site of abd-A, and the iab-8 RNA primary transcript likely continues past its poly(A) addition site [38]. In any case, minor splice variants

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Figure 5. Test for trans repression by the iab-8 ncRNA. CNS’s, stained for ABD-A, were dissected from embryos of the indicated genotypes. In iab-8 mfs5649 embryos, only one chromosome makes a full length iab-8 ncRNA, and neither chromosome produces the iab-8 miRNA, as diagrammed. The strong expression of ABD-A in PS15 in this genotype shows that the abd-A gene on the mfs5649 chromosome is not repressed, i.e. the iab-8 ncRNA acts only in cis.
clearly do continue past the poly(A) site and into the abd-A transcription unit (Figure 2).

The function of the iab-8 ncRNA fits with the rule of posterior dominance - it blocks expression of a more anterior homeotic gene in more posterior segments. The repression of Ubx by the bad ncRNA [10], although subtle, fits the same pattern. The novel aspect, here, is that this posterior repression can be accomplished by noncoding transcription units, in addition to DNA binding proteins. The mechanism of transcriptional interference would dictate the linear order of the anterior genes by readthrough transcripts of more posterior genes, or by noncoding RNAs initiating from their posterior enhancers. Such a method of repression would dictate the linear order of the HOX genes, 3’ to 5’, anterior to posterior.

Materials and Methods

Drosophila strains

Wild type stocks were Canton S or Oregon R. Mutations included abd-A\textsuperscript{AMX}, iab-9\textsuperscript{527}, iab-10\textsuperscript{G12}, iab-5\textsuperscript{G43}, iab-7\textsuperscript{GAC62}, abd-B\textsuperscript{D109}, abd-B\textsuperscript{H14}, Df(3R)C4, Df(3)P9 [ref [39]]; iab-3\textsuperscript{G3}, iab-5\textsuperscript{G11} (ref [17]) iab-6\textsuperscript{G11} [ref [40]]; Fab7\textsuperscript{H} ref [41]; mfs(3)50649 [ref [25], Fab9\textsuperscript{H} ref [22]; Fab8\textsuperscript{G1} ref [42]; iab-5\textsuperscript{G10}; iab-4\textsuperscript{G10}; iab-5\textsuperscript{G43}, iab-5\textsuperscript{G43}, iab-5\textsuperscript{G43}, ΔMiR-iab-9 [ref [11]]; T(3;2)DpD109 [28] and Mi/Hwo-WP (described here).

Antibody staining

Embryos were fixed, stained, and mounted as described by [17]. Primary antibodies used were mouse anti-ABD-B (1:2 dilution, developed by S. Celinker, Developmental Studies Hybridoma Bank), mouse anti-UBX (1:10, developed by R. White, Developmental studies Hybridoma Bank), rabbit anti-β-galactosidase (1:1500, Cappel/MP Biomedicals), mouse anti-β-galactosidase (1:1000, Promega), rabbit anti-En (1:500, 6A18.12, gift of I. Duncan), and goat anti-ABD-A (1:100, Santa Cruz Biotechnology). Secondary antibodies were donkey anti-mouse, donkey anti-goat, and donkey anti-rabbit, coupled to either Alexa 488 or Alexa 555 (1:500, Invitrogen), and HRP coupled goat anti-mouse (1:1000, Bio-Rad).

The CNS’s were hand dissected with tungsten needles and placed on a glass slide in a drop of Immu-Mount (for HRP staining, Shandon) or Vectashield with DAPI (for fluorescence, Vector Laboratories), and then gently flattened under a coverslip. Fluorescence images were taken with a Leica SP2 AOBS confocal microscope; the fluorescence pictures show free projection averages of stacks of images, after scanning through the depth of the tissue. Homozygous embryos were identified by the absence of lacZ staining from the T\textsuperscript{M3} 5’z-Lac\textsuperscript{z} balance.

Fertility tests

Each of ten mutant virgin females was placed in a vial with three wild type males. Likewise ten mutant males were mated, each with three wild type virgin females. Vials were maintained at 25°C for five days, and then examined for the presence of larvae.

cDNA analysis

Adults heterozygous for Mi/Hwo-WP and Hsp\textsuperscript{70}Gal4 (Bloomington stock #1799) were heat shocked for 45 min. at 37°C to induce GAL4 expression, and then left to express the LNP transcript at room temperature for 4 h. RNA was then isolated using TRI reagent (Sigma) and reverse transcribed with MMLV reverse transcriptase (Promega) using an adaptor primer (GAGACAGACACCGGACT18V). PCR was then performed using a forward primer in Hto and a reverse primer in the 6th exon of abd-A. The resulting amplicon was sequenced to identify the splicing pattern.

Total RNA from Oregon R embryos was prepared using the RNAqueous-4PCR kit (Ambion), and 3’ RACE and RNA ligase-mediated 5’ RACE reactions were performed using the First-Choice RLM-RACE kit (Ambion). The 5’ RACE procedure was designed to recover only capped 5’ ends. Gel-isolated products were sequenced directly, or cloned first into the PCR-Blunt vector (Invitrogen). Quantitative PCR reactions used cDNA prepared from 6–12 h old embryos. The initial cDNA products were compared to measured dilutions of amplified cDNA products covering the relevant exons.

RNA in situ hybridization and embryo staining

The production of digoxigenin-labeled probes and the hybridization of embryos was as described by Fitzgerald and Bender [11], except that acetone treatment [43] was used instead of proteinase K for permeabilization of the embryos. Clones spanning exon 8 from D. melanogaster, D. pseudobscura and D. viridis were recovered after PCR reaction on genomic DNAs with the following pairs of oligonucleotides: D. melanogaster 5’ CGCTCGAGATTACAAACGG3’ and 5’ GGTGTAATACGGTCAGGGG3’ generating a fragment of 1013 bp; D. pseudobscura 5’ CAGGACCATTCAATACACCGGC3’ and 5’ GAGATGTGTCGAGTTGGTGG3’ generating a fragment of 1477 bp; D. viridis 5’ CTCTTCGGTCTATTCACACGG3’ and 5’ CCGATCCGTGTTGGC3’ generating a fragment of 1364 bp.

Supporting Information

Figure S1 Sequences of iab-8 ncRNA exons. The first and last bases of each exon are numbered according to the SEQ89E coordinates of Martin et al. [4] (Genbank U31961). (PDF)

Figure S2 Conserved iab-8 noncoding RNA expression patterns in D. melanogaster, D. pseudobscura and D. viridis embryos. The top 3 panels show embryos at stage 8, while the bottom panels show embryos at stages 14–17. (TIF)

Figure S3 Additional test for repression by the iab-8 ncRNA. Males of the genotype T(2;3) DpD109, AmiR, Fab/TM2 were crossed to ΔmiR/TM3, 5’z-Lac\textsuperscript{z} females. The TM3-containing embryos were recognized by their LacZ expression. Among the remaining embryos, half showed no apparent ABD-B expression in the CNS of PS13 (presumed to be T(2;3) DpD109, AmiR/TM3, 5’z-Lac\textsuperscript{z}). Thus, the repression fails to act in trans on the duplication. The PS13 misexpression is weaker than the PS7-12 level, because the former derives from only the one ABD-A copy on the duplication, while the latter represents three doses of the abd-A gene. DpD109, +/AmiR embryos produced in a control cross displayed little, if any, ABD-B misexpression in PS13. (TIF)

Table S1 Two mechanisms, iab-8 miRNA trans-repression and cis-repression mediate abd-A repression in PS13 of the CNS. The table summarizes which of these 2 mechanisms is/are affected in the various mutant alleles. Note that complete ectopic expression in PS13 is only observed when both mechanisms are affected. (TIF)
**References**


**Author Contributions**

Conceived and designed the experiments: MG RMK HG SS KA FK WB. Performed the experiments: MG HG JCA SS KA FK WB. Analyzed the data: MG RMK HG SS KA FK WB. Contributed reagents/materials/analysis tools: MG JCA RMK HG SS KA FK WB. Wrote the paper: MG RMK KA FK WB.