AP endonuclease EXO-3 deficiency causes developmental delay and abnormal vulval organogenesis, Pvl, through DNA glycosylase-initiated checkpoint activation in Caenorhabditis elegans

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AP endonuclease deficiency causes cell death and embryonic lethality in mammals. However, the physiological roles of AP endonucleases in multicellular organisms remain unclear, especially after embryogenesis. Here, we report novel physiological roles of the AP endonuclease EXO-3 from larval to adult stages in Caenorhabditis elegans, and elucidated the mechanism of the observed phenotypes due to EXO-3 deficiency. The exo-3 mutants exhibited developmental delay, whereas the apn-1 mutants did not. The delay depended on the DNA glycosylase NTH-1 and checkpoint kinase CHK-2. The exo-3 mutants had further developmental delay when treated with AP site-generating agents such as methyl methane sulfonate and sodium bisulfite. The further delay due to sodium bisulfite was dependent on the DNA glycosylase UNG-1. The exo-3 mutants also demonstrated an increase in dut-1 (RNAi)-induced abnormal vulval organogenesis protruding vulva (Pvl), whereas the apn-1 mutants did not. The increase in Pvl was dependent on UNG-1 and CHK-2. Methyl viologen, ndx-1 (RNAi) and ndx-2 (RNAi) enhanced the incidence of Pvl among exo-3 mutants only when combined with dut-1 (RNAi). This further increase in Pvl incidence was independent of NTH-1. These results indicate that EXO-3 prevents developmental delay and Pvl in C. elegans, which are induced via DNA glycosylase-initiated checkpoint activation.

AP endonucleases are enzymes that function in the repair of DNA damage such as apurinic/apyrimidinic (AP) sites or single-strand breaks with 3′-blocked ends (3′-blocked SSB) in DNA1,2. AP sites are generated by the spontaneous hydrolysis of purine/pyrimidine bases (depurination/depyrimidination) or through the DNA glycosylase activity of monofunctional DNA glycosylases, which cleave N-glycosidic bonds in DNA3,4. Bifunctional DNA glycosylases, which possess both DNA glycosylase activity and AP lyase activity, generate 3′-blocked SSB by cutting N-glycosidic bonds in DNA and subsequently nicking the sugar phosphate backbone at AP sites1. Through the process of DNA replication, AP sites and 3′-blocked SSB can cause double-stranded breaks (DSB), which are considered to be the most deleterious form of DNA lesions and can lead to cell death if not repaired properly5,6. Therefore, the repair of AP sites and 3′-blocked SSB is important to protect cells and organisms against their adverse effects. AP sites and 3′-blocked SSB are processed by different enzymatic activities of AP endonucleases, AP endonuclease activity and 3′-phosphodiesterase activity, respectively1,7. Both activities generate SSB with 3′-OH ends, which are required for the subsequent steps of the repair process known as base excision repair (BER), which is carried out by DNA polymerases and DNA ligases7.

The in vivo roles of AP endonucleases in unicellular organisms have been well studied. Insufficient AP endonuclease activity in unicellular organisms, including Escherichia coli (E. coli) and Saccharomyces cerevisiae (S. cerevisiae), has been shown to cause cell death and embryonic lethality

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Caenorhabditis elegans (C. elegans) is a useful model animal to study the physiological roles of AP endonucleases. Worms deficient in AP endonuclease genes do not exhibit embryonic lethality and can become fertile adults\(^1\). Therefore, the physiological effects of the lack of AP endonucleases can be assessed throughout life. In C. elegans, two AP endonucleases, EXO-3 and APN-1, have been identified\(^2\). EXO-3 and APN-1 are encoded by the exo-3 and apn-1 genes, respectively. EXO-3 is a homolog of mammalian APE1, but the redox regulatory domain is not conserved\(^3\). A series of in vitro experiments revealed that both EXO-3 and APN-1 have AP endonuclease activity and 3′-phosphodiesterase activity\(^4,5\). Malfunction of AP endonucleases causes severe phenotypes in C. elegans. Exo-3 (RNAi) worms have a reduced life-span in a cep-1 (C. elegans p53 ortholog)-dependent manner\(^6\). Exo-3 mutant worms also exhibit a shortened life-span and reduced self-brood size\(^7\). Apn-1 (RNAi) worms have a moderately reduced longevity only when they are exposed to DNA damaging agents\(^8\). Apn-1 (RNAi) worms also demonstrate retardation of the division of the P1 blastomere\(^9\). Studies conducted thus far have focused on worms before the larval stages or after the adult stages\(^10\). However, the contribution of AP endonucleases during the larval to adult stages remains poorly understood.

To investigate the physiological roles of AP endonucleases from the larval to adult stages in C. elegans, we assessed the impact of AP endonuclease deficiency on development and vulval organogenesis from the larval to adult stages in C. elegans. We report newly identified phenotypes of exo-3(tm4374) mutants: developmental delay and increased dut-1 (RNAi)-induced abnormal vulval organogenesis. We also present evidence that these phenotypes are induced through a common mechanism where DNA glycosylases initiate DNA damage checkpoint activation.

**Results**

**The expression level of AP endonucleases increases after the L4 stage.** After hatching, C. elegans develop into adults through four larval stages (L1–L4), each punctuated by molting of the cuticle. Adult stages are still subdivided into two stages: the young adult stage and the gravid adult stage. To gain insight into the role of AP endonucleases after embryogenesis, we measured the temporal change in the mRNA expression level of exo-3 or apn-1. At 0, 24 and 48 hours, when most N2 worms are in the egg stage, L1 stage and L4 stage, respectively, no difference in mRNA expression level was found for both exo-3 and apn-1 (Fig. 1a,b). At 60 hours, when most N2 worms are in the young adult stage, the exo-3 and apn-1 expression levels were approximately 13-fold and 2.3-fold higher than those at 0 hours, respectively (Fig. 1a,b). The expression level at 72 hours, when most N2 worms are in the gravid adult stage, was the same at 60 hours (Fig. 1a,b). These results suggest that AP endonucleases are required after embryogenesis, especially after the L4 stage.

**The exo-3 mutants exhibit developmental delay.** To clarify the contribution of AP endonucleases to worm development from the L4 to adult stages, worms deficient in either or both AP endonucleases (EXO-3 and APN-1) were incubated under normal rearing conditions for 3 days from the fertilized egg stage (Fig. 1c). Developmental stages among the L4, young adult and gravid adult stages were distinguished by the state of vulval morphology and brooding of eggs (Fig. 1d,f). Although all of the N2 worms developed into gravid adults, only 14% of the exo-3 mutants were in the gravid adult stage, 85% were in the young adult stage and 1% was in the larval stage (Fig. 1g), suggesting that EXO-3 deficiency causes the cessation of development or developmental delay. In contrast, all of the apn-1 mutants became gravid adults, and the apn-1;exo-3 mutants were at almost the same developmental stages as the exo-3 mutants (Fig. 1g). Twelve hours later, all the exo-3 and apn-1;exo-3 mutants reached the gravid adult stage (data not shown), indicating that EXO-3 deficiency does not cause cessation of development at the young adult stage, only developmental delay. To precisely investigate how long the delay of the exo-3 mutants was, we measured the reaching time to gravid adult of each worm every two hours and calculated the difference of the average time between N2 (N = 8) and the exo-3 mutants (N = 16). The difference was 6 hours.

**The developmental delay in the exo-3 mutants is dependent on the DNA glycosylase NTH-1.** It is reasonable to infer that the developmental delay phenotype of exo-3 mutants is caused by the accumulation of AP sites or 3′-blocked SSB in DNA because these are substrates for EXO-3\(^15\). These structures in DNA can be generated by DNA glycosylases. Of the two DNA glycosylases conserved in C. elegans, UNG-1 generates AP sites through monofunctional DNA glycosylase activity on uracil in DNA, and NTH-1 produces 3′-blocked SSB via bifunctional DNA glycosylase activity on oxidative pyrimidine lesions in DNA. Therefore, we examined the dependency of the delay in the exo-3 mutants on UNG-1 and NTH-1. Three days after developing from eggs, 9% of the ung-1;exo-3 mutants were in the gravid adult stage, 86% were in the young adult stage and 5% were in the larval stage, and these proportions were almost the same as those shown by the exo-3 mutants (11% in the gravid adult stage, 85% in the young adult stage and 4% in the larval stage) (Fig. 2), suggesting that the delay is...
independent of UNG-1. In contrast, 94% of the nth-1;exo-3 mutants were in the gravid adult stage and 6% were in the young adult stage. The nth-1;ung-1;exo-3 mutants exhibited similar results (Fig. 2), suggesting that the delay is dependent on NTH-1.

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**Figure 1.** Effects of AP endonuclease deficiency on larval development of worms under normal rearing conditions. (a,b) At each time point after birth, N2 worms were harvested, and the total RNA isolated from the worms was subjected to real-time PCR analysis using specific primer sets for exo-3 (a) and apn-1 (b). As an internal control, Y45F10D.4 was used. The values represent the mean ± S.E. (n = 3/each time point). (c) Experimental scheme. (d–f) Representative images of worms at each developmental stage. L4 larvae (d). Young adults (e). Gravid adults (f). Black arrows indicate the vulval position. Developmental stages were assessed based on vulval morphology and brooding of eggs. (g) Proportion of worms at each developmental stage after 3 days of incubation of fertilized eggs. The values indicate the number of worms at each developmental stage/the number of total surviving worms.

**Figure 2.** Effects of DNA glycosylase deficiency on larval development of exo-3 (tm4374) mutant worms under normal rearing conditions. Proportion of worms at each developmental stage after 3 days of development from eggs. The values indicate the number of worms at each developmental stage/the number of total surviving worms.
The developmental delay of the exo-3 mutants is enhanced by MMS and NaHSO₃.

To clarify whether AP site-generating agents can cause developmental delay, we conducted a developmental assay using MMS and sodium bisulfite (NaHSO₃) (Fig. 3a). MMS is known to indirectly create AP sites²⁰,²¹ and shown to induce DNA lesions in the genome of C. elegans²². At 3.5 days after the eggs were laid on plates containing 0.94 mM MMS, 97% of N2 were in the gravid adult stage and 3% were in the larval stage, whereas 61% of the exo-3 mutants were in the gravid adult stage, 34% were in the young adult stage and 5% were in the larval stage (Fig. 3b), suggesting that MMS-induced AP sites cause further developmental delay in the exo-3 mutants than in N2. On the other hand, 93% of the apn-1 mutants were in the gravid adult stage, 6% were in the young adult stage and 1% were in the larval stage, which is similar to the results for N2 (Fig. 3b). NaHSO₃ damages DNA mainly through deamination of cytosine to uracil²³. Four days after developing from the egg stage, all exo-3 mutants not treated with NaHSO₃ developed into gravid adults, but 33% of those treated with 10 mM NaHSO₃ were in the gravid adult stage, 12% were in the young adult stage and 55% were in the larval stage (Fig. 3c), indicating that NaHSO₃ induced developmental delay in the exo-3 mutants. This delay was alleviated in the ung-1;exo-3 mutants, as 79% of those treated with 10 mM NaHSO₃ were in the gravid adult stage, 14% were in the young adult stage and 7% were in the larval stage (Fig. 3c), suggesting that the NaHSO₃-induced developmental delay was due to UNG-1 activity. Taken together, AP sites may cause developmental delay as well as 3′-blocked SSB generated by NTH-1.

The developmental delay of the exo-3 mutants is induced by CHK-2.

We next hypothesized that the DNA glycosylase-initiated developmental delay of the exo-3 mutants was due to DNA damage checkpoint activation driven by cleavage products produced by DNA glycosylases. DNA damage checkpoint genes, such as chk-2 and clk-2, have been described in C. elegans²⁴. To test our hypothesis, the developmental assay was conducted under clk-2 (RNAi) or clk-2 (RNAi) conditions (Fig. 4a). Although 14% of the exo-3;control (RNAi) worms were in the gravid adult stage and 84% were in the young adult stage, and exo-3;clk-2 (RNAi) worms demonstrated similar proportions (18% in the gravid adult stage and 82% in the young adult stage), 93% of the exo-3;chk-2

Figure 3. Effects of AP site-generating agents on larval development of worms. (a) Experimental scheme. (b,c) Proportion of worms at each developmental stage 3.5 and 4 days after developing from eggs under 0.94 mM MMS (b) and 10 mM NaHSO₃ (c) conditions, respectively. The values indicate the number of worms at each developmental stage/the number of total surviving worms.
(RNAi) worms were in the gravid adult stage (Fig. 4b). Thus, the knockdown of chk-2 rescued the developmental delay in the exo-3 mutants, suggesting that CHK-2 induces the developmental delay in the exo-3 mutants.

EXO-3 prevents dut-1 (RNAi)-induced Pvl formation. Dut-1 is a deoxyuridine triphosphate nucleotidohydrolase (dUTPase), which hydrolyzes dUTP into dUMP. Therefore, dut-1 (RNAi) leads to increased dUTP in the nucleotide pool, which is incorporated into DNA through DNA replication instead of dTTP, causing the accumulation of uracil in DNA25,26. It has been reported that dut-1 (RNAi) induces abnormal vulval organogenesis, Pvl, in wild-type N2 worms, and that the dut-1 (RNAi)-induced Pvl is dependent on UNG-127. We speculated that EXO-3 deficiency causes an increase in the incidence of dut-1 (RNAi)-induced Pvl because EXO-3 is needed to repair AP sites after the cleavage of uracil in DNA by UNG-1. To confirm this, dut-1 (RNAi)-induced Pvl formation was observed in AP endonuclease-deficient mutants (Fig. 5a–c). Of the surviving adults 4 days after developing from eggs, 52% were exo-3 mutants with dut-1 (RNAi)-induced Pvl and 13% were N2 worms with Pvl (Fig. 5d), suggesting that EXO-3 deficiency causes an increase in dut-1 (RNAi)-induced Pvl. On the other hand, 15% of the apn-1 mutants had Pvl, which is similar to the proportion of N2 worms with Pvl (Fig. 5d). The apn-1;exo-3 mutants and exo-3 mutants were similar in proportion, with 52% having Pvl (Fig. 5d).

The increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants is dependent on UNG-1 irrespective of NTH-1. To examine whether the increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants occurred through UNG-1 activity, we investigated the dependency of the phenotype on UNG-1. The percentage of ung-1;exo-3 mutants with Pvl was 2%, which was the same as that of the ung-1 mutants with Pvl (1%) (Fig. 6a), suggesting that the increase in Pvl in the exo-3 mutants is only due to UNG-1 expression.

Next, we examined whether the cleavage products produced by UNG-1 are needed to induce Pvl, i.e., whether AP sites are transformed into 3’-blocked SSB via the AP lyase activity of NTH-1. The percent of exo-3 mutants with Pvl was comparable to that of nth-1;exo-3 mutants (Fig. 7b), suggesting that NTH-1 is not necessary for dut-1 (RNAi)-induced Pvl.

The increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants is driven by CHK-2. We hypothesized that the UNG-1-dependent increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants can occur via DNA checkpoint activation driven by cleavage products produced by UNG-1 in addition to developmental delay. It has also been reported that dut-1 (RNAi)-induced Pvl is caused by the checkpoint kinase CLK-225. Therefore, we examined whether the increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants was dependent on CHK-2 and CLK-2. Although 49% of exo-3;control (RNAi) worms had dut-1 (RNAi)-induced Pvl, only 10% of the exo-3;chk-2 (RNAi) worms had it (Fig. 6b). On the other hand, the proportion of exo-3;clk-2 (RNAi) worms with Pvl was almost the same (44%) as that of the exo-3;control (RNAi) worms. Therefore, the knockdown of chk-2 rescued the increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants, as observed for developmental delay. These results suggest that the increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants occurs via CHK-2 expression.

Oxidative DNA damaging agents enhanced the proportion of Pvl in the exo-3 mutants only when combined with dut-1 (RNAi). To investigate other DNA damaging agents that cause an increase in
Pvl in the exo-3 mutants, we evaluated whether Pvl formation is enhanced by oxidative DNA damaging agents such as ndx-1 (RNAi), ndx-2 (RNAi) and methyl viologen (MV). NDX-1 and NDX-2 hydrolyze 8-oxo-dGDP into 8-oxo-dGMP. Accordingly, ndx-1 (RNAi) and ndx-2 (RNAi) lead to an increase in 8-oxo-dGDP in the nucleotide pool. The presence of 8-oxo-dGDP reduces the 8-oxo-dGTPase activity of NDX-4, causing 8-oxo-dGTP to accumulate in the pool. 8-oxo-dGTP is incorporated to DNA during DNA replication, resulting in the accumulation of 8-oxoG in DNA. MV generates superoxide radicals, which subsequently cause oxidative lesions in DNA. However, single treatment with ndx-1 (RNAi), ndx-2 (RNAi) or MV had no effect on the incidence of Pvl in the exo-3 mutants. (data not shown). Next, we examined whether, when combined with the dut-1 (RNAi) treatment, each oxidative DNA damaging agent further enhanced the increase in Pvl in the exo-3 mutants (Fig. 7a).

Each treatment tested enhanced the increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants by approximately 10% (Fig. 7b), suggesting that oxidative lesions in DNA can also cause an increase in Pvl.

In in vitro experiments, NTH-1 was found to possess weak DNA glycosylase activity toward 8-oxoG in DNA, in addition to its much higher activity toward oxidative pyrimidine lesions. Thus, we suspect that the higher increase in dut-1 (RNAi)-induced Pvl by the additional oxidative agents depends on the activity of NTH-1. Although we confirmed the dependency of the phenotype on NTH-1, NTH-1 deficiency did not alter the proportion of worms exhibiting Pvl (Fig. 7b).

Discussion

In this study, we investigated the in vivo contribution of AP endonucleases from the larval to adult stages in C. elegans by evaluating development and vulval organogenesis in AP endonuclease gene mutants, and clarified that AP endonuclease EXO-3 deficiency causes developmental delay and an increased incidence of dut-1 (RNAi)-induced Pvl via DNA glycosylase-initiated checkpoint activation (Fig. 8).

The exo-3 mutants demonstrated developmental delay, whereas the apn-1 mutants did not (Fig. 1e), suggesting that EXO-3 has a more important role than APN-1 during development from the larval to adult stages. The delay in the exo-3 mutants was completely dependent on NTH-1 (Fig. 2), suggesting that it is caused by 3′-blocked SSB generated by NTH-1. We therefore hypothesized that AP sites cannot cause developmental delay in the exo-3 mutants. However, MMS and NaHSO₃ induced further developmental delay in the exo-3 mutants (Fig. 3b,c), and we found that the delay by NaHSO₃ was dependent on UNG-1 (Fig. 3c), suggesting that AP sites also caused developmental delay in the exo-3 mutants, although the further delay may be caused by a mixture of both AP sites and cleaved AP sites with 3′-blocked SSB by NTH-1.

The developmental delay in the exo-3 mutants was also due to CHK-2 (Fig. 4b). CHK-2 is an ortholog of mammalian Chk2, which is activated in response to several DNA damaging agents that cause DSB, but there is no direct evidence that C. elegans CHK-2 is involved in a checkpoint mechanism driven by SSB. As 3′-blocked SSB can generate DSB during DNA replication, as well as AP sites, it is possible that the resulting DSB activated the CHK-2 response, thereby leading to developmental delay. It was recently reported that ATM, which positively

Figure 5. Effects of AP endonuclease deficiency on dut-1 (RNAi)-induced Pvl. (a) Experimental scheme. (b,c) Representative images of vulva of control worms (b) and dut-1 (RNAi)-induced Pvl worms (c). (d) Proportion of Pvl worms 4 days after development from eggs. The values indicate the number of Pvl worms/number of adult worms.
regulates Chk2 activity in response to DSB-generating agents\textsuperscript{33,34}, is also activated by SSBs in human cells\textsuperscript{35}. Thus, it is possible that 3′-blocked SSB directly activate CHK-2 via an ATM-1/CHK-2 pathway.

The exo-3 mutants exhibited an increased incidence of dut-1 (RNAi)-induced Pvl (Fig. 5d), but the apn-1 mutants did not, suggesting that EXO-3 has a more important role than APN-1 in vulval organogenesis and development. The increase in Pvl in the exo-3 mutants was completely dependent on UNG-1 (Fig. 6a). This suggests that Pvl is caused by UNG-1-generating AP sites. The increase in Pvl occurred irrespective of NTH-1 (Fig. 7b), suggesting that the transformation of AP sites into 3′-blocked SSB by NTH-1 is not needed to induce the increase in Pvl.

Dengg et al. previously reported that dut-1 (RNAi)-induced Pvl occurs via the checkpoint kinase CLK-2\textsuperscript{27}. CLK-2 may be activated by replication fork collapse-mediated DSB because they found that dut-1(RNAi) enhances the accumulation of RPA-1, ATL-1 (ATR ortholog in C. elegans) and RAD-51 in mitotic germ cells based on UNG-1 activity\textsuperscript{27}. In this study, we tried to clarify whether the increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants was dependent on CLK-2, but knockdown of CLK-2 had no effect on the increased incidence of Pvl (Fig. 6b). This discrepancy may result from the methods used to compromise CLK-2 function. Dengg et al. used clk-2 mutant worms, whereas we used clk-2 (RNAi) worms, as reported previously\textsuperscript{24}. Instead of CLK-2, another checkpoint kinase, CHK-2, was found to be a causal factor of the increase in Pvl (Fig. 6b). It is possible that a mechanism similar to CLK-2 activation causes Pvl formation through CHK-2 in the exo-3 mutants.

The increase in dut-1 (RNAi)-induced Pvl in the exo-3 mutants was further enhanced by oxidative DNA damaging agents such as ndx-1 (RNAi), ndx-2 (RNAi) and MV (Fig. 7b). The damaging agents may have only caused Pvl in the exo-3 mutants when combined with dut-1 (RNAi) because of a threshold of DNA lesions needed for Pvl. Combining each oxidative damaging agent with dut-1 (RNAi) results in more DNA lesions containing 8-oxoG than single dut-1 (RNAi) treatment. However, a direct homolog of MutM or OGG1 cannot be detected in C. elegans. As a candidate protein to incise 8-oxoG in DNA in vivo in C. elegans, we examined NTH-1. However, the effects of ndx-1 and ndx-2 knockdown on Pvl were independent of NTH-1 (Fig. 7b). A novel DNA glycosylase that can incise 8-oxoG may be responsible for this phenotype, but further studies are needed.

Pvl is formed by prevention of ras/notch/wnt signaling pathway\textsuperscript{36–38}. We demonstrated that the checkpoint activation caused by UNG-1 results in the induction of Pvl, while the downstream pathway to induce Pvl still
remains unclear. Thus, it is possible that checkpoint activation affects Pvl induction through modulation of other pathways such as ras/notch/wnt signaling pathways. However, there is no evidence of the link between checkpoint activation and such signaling pathways.

It is reasonable that checkpoint activation causes developmental delay, while it seems paradoxical that the activation also causes Pvl induction. The reason for the point is that developmental delay induced by checkpoint activation is predicted to be a mechanism for preventing mutagenesis, which provides worms beneficial effects. In contrast, Pvl caused by the activation seems to have no valuable effects. However, it is probable that the induction of Pvl, resulting in egg-laying-defective (Egl) worms, is a mechanism for preventing the accumulation of mutations in the next generation.

This study demonstrated that EXO-3 prevents DNA glycosylase-initiated checkpoint activation in order for worms to grow at a normal speed and with normal vulva. Although there have been many studies reported a correlation between BER and biological phenomena, such as carcinogenesis and aging, few studies demonstrating...
causation have been conducted\textsuperscript{38,40}. Due to the availability of \textit{C. elegans} mutants and the characteristics of \textit{C. elegans} mutants lacking AP endonucleases enabling them to mature past embryonic stages and produce the next generation, we were able to examine causal relationships between BER and many biological phenomena throughout life. Further studies on AP endonucleases using \textit{C. elegans} will provide more detailed information about the \textit{in vivo} roles of AP endonucleases in multicellular organisms.

**Methods**

**\textit{C. elegans} strains and culture conditions.** The wild-type strain (Bristol N2) and RB877 \textit{[nth-1(ok724) III]}\textsuperscript{38} were obtained from the Caenorhabditis Genetics Center, University of Minnesota. TM4374 \textit{[exo-3(tm4374) I]}\textsuperscript{41}, TM6691 \textit{[apn-1(tm6691) II]}\textsuperscript{14} and TM2862 \textit{[ung-1(tm2862) III]}\textsuperscript{42} were supplied by the National Bioresource Project for the Nematode (Tokyo Women's Medical College). All mutants were backcrossed with N2 worms at least 3 times to remove background mutations, and the homozygous mutant progeny were used in the following experiments. The \textit{apn-1:exo-3, nth-1:exo-3, ung-1:exo-3 and nth-1:ung-1:exo-3} mutants were generated by crossing each strain. Deletion in the \textit{exo-3}, \textit{apn-1}, \textit{nth-1} and \textit{ung-1} genes was confirmed by PCR utilizing the same 2 primer pairs from a previous study\textsuperscript{41}. In general, worms were cultured at 20 °C on NGM agar plates containing 0.3% (w/v) NaCl, 0.25% (w/v) polypeptone, 0.005% (w/v) cholesterol, 1 mM MgSO\textsubscript{4}, 1 mM CaCl\textsubscript{2} and 25 mM potassium phosphate, at pH 6.0 with 0.17% (w/v) agar and a lawn of \textit{Escherichia coli (E. coli)} OP50.

**Synchronization of worms.** To obtain synchronized eggs, we made gravid adult worms lay eggs for approximately 2 hours on the same plates used for subsequent assays. Synchronized eggs were transferred to new plates for each assay.

**Bacteria-mediated RNA interference.** For knockdown experiments, we used a well-established RNA interference (RNAi) method\textsuperscript{13,39}. \textit{C. elegans dat-1, ndx-1, ndx-2, chk-2 (Y60A3A.12) and clk-2 (C07H6.6)} complementary DNA (cDNA) clones were amplified by PCR from a cDNA library using the same 2 primer pairs from a previous study.\textsuperscript{24,38} The amplified PCR products were subcloned into the plasmid L4440 for bacteria-mediated RNA interference (RNAi) plasmid. Double RNAi experiments were performed by mixing an equal amount of overnight cultures of \textit{E. coli} HT115 (DE3) that had been transformed with the respective RNAi plasmids, and then plating the mixture on NGM plates containing 0.1 mM IPTG and 100 μg/ml ampicillin (RNAi plates)\textsuperscript{24}. As a negative control for RNAi, the transformant harboring L4440 was used.

**Measurement of developmental speed.** To assay the effects of AP endonuclease deficiency on larval development, synchronized eggs were placed on normal NGM plates, NGM plates containing 0.94 mM MMS or 10 mM NaHSO\textsubscript{3} or RNAi plates. After incubation at 20 °C for 3, 3.5 (MMS) or 4 (NaHSO\textsubscript{3}) days, developmental stages of surviving worms were assessed based on vulval morphology and brooding of eggs to distinguish young adult worms from gravid adult worms. The proportion of worms at each developmental stage among the total number of surviving worms was calculated.

**Measurement of the proportion of Pvl worms.** To assay the effects of AP endonuclease deficiency on organogenesis, synchronized eggs were placed on \textit{dat-1 (RNAi) plates} (plus additional RNAi and 0.1 mM methyl viologen (MV), if necessary). After incubation at 20 °C for 4 days, the numbers of total adult worms and Pvl worms were counted, and the proportion of Pvl worms among adult worms was calculated. Significance was determined using one-way ANOVA with Tukey’s test for multiple comparisons.

**Microscopy.** Observation and imaging of \textit{C. elegans} were performed using an OLYMPUS SZX16 microscope (OLYMPUS, Japan).

**Real-time PCR analysis.** Worms (N2 at 0, 24, 48, 60 or 72 hr) were collected and lysed using TriPure isolation reagent (Roche, Basel, Switzerland). Then, total RNA was extracted from the above supernatant with NucleoSpin RNA (Takara Bio, Shiga, Japan), as recommended by the manufacturer. First-strand cDNA was synthesized from total RNA using oligo-dT primer and ReverTra Ace (Toyobo, Osaka, Japan). Real-Time PCR was performed using Light-Cycler 96 (Roche) with THUNDERBIRD SYBER qPCR Mix (Toyobo, Osaka, Japan). The thermal cycler conditions were as follows: an initial denaturation step at 95 °C for 60 sec, followed by 45 three-step PCR cycles of 95 °C for 15 sec, 60 °C for 30 sec and 72 °C for 45 sec. Gene amplification specificity was confirmed by melting curve analysis. The following are the primer sequences: APN1, 5′-GCTATCAGAAATGAGAAGCA-3′ and 5′-TCCAGTTTAGAGGTTTCTTC-3; EXO3, 5′-CGGAGATGGAGGAGACGTTTA-3′ and 5′-TCTGGG TCACCGATTCTTTG-3; Y45F10D.4, 5′-CGAGAACCCCGGAAATGTCGGA-3′ 5′-GCTCTATCCTTCC CTGGCACC-3′. The two-tailed Student’s t-test was used for statistical analysis.

**Data Availability**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author Contributions
M.M. and Q.Z. designed the project. M.M. designed experiments. M.M., Y.H., M.F. and A.T. performed research. All authors contributed to the analysis of the results. M.M. drafted the manuscript, and all authors refined the manuscript. All authors read and approved the final manuscript.

Additional Information
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