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An Experimental Assessment of the Cause of Mummification in the Joseon Period Burials, Republic of Korea

This article presents the results of experiments aimed at testing the hypothesis that the mummification of human bodies in Joseon Dynasty burials was caused by an exothermic reaction and the consequent destruction of intestinal flora. Well-preserved mummies of that period were discovered only in the Hoegwakmyo tombs, where the lime-soil-mixture barrier was present. Experiments were conducted using animals' bodies placed in miniature grave models. Immediately after contact with moisture, the temperature inside the coffin surrounded by a lime-soil-mixture increased to $130.8 \pm 23.5^\circ\text{C}$ and remained stable for 141.0 ± 64.7 minutes. The examination of bacterial cultures on MacConkey or blood agar plates showed that the entire flora normally existing in the rat's intestine was completely sterilized by high temperature. We also demonstrate that the same mummification can be reproduced regardless of the sizes of miniature graves.

Keywords: Korea, mummies, Joseon, experiment, animals, lime-soil mixture, Hoegwakmyo.

Korean Mummies of the Joseon Period

Well-preserved Korean mummies have been discovered during the past several decades in tombs of the Joseon Dynasty (1392–1910 AD) (Fig. 1, A). One of the most important characteristics we have noticed of Korean mummies is their near-perfect status of preservation

(Fig. 1, B) as compared to those found in other countries. Certainly, well-preserved Joseon mummies have yielded invaluable information to scholars, though the latter have also encountered internal organs, the morphologies of which had been deformed by dehydration and long-acting gravitational forces (Shin et al., 2003; Kim et al., 2006) (Fig. 1, C).

The Korean mummies have been extensively studied by interdisciplinary research teams in South Korea (Shin et al., 2003; Kim et al., 2006; Lee et al., 2013; Seo et al.,

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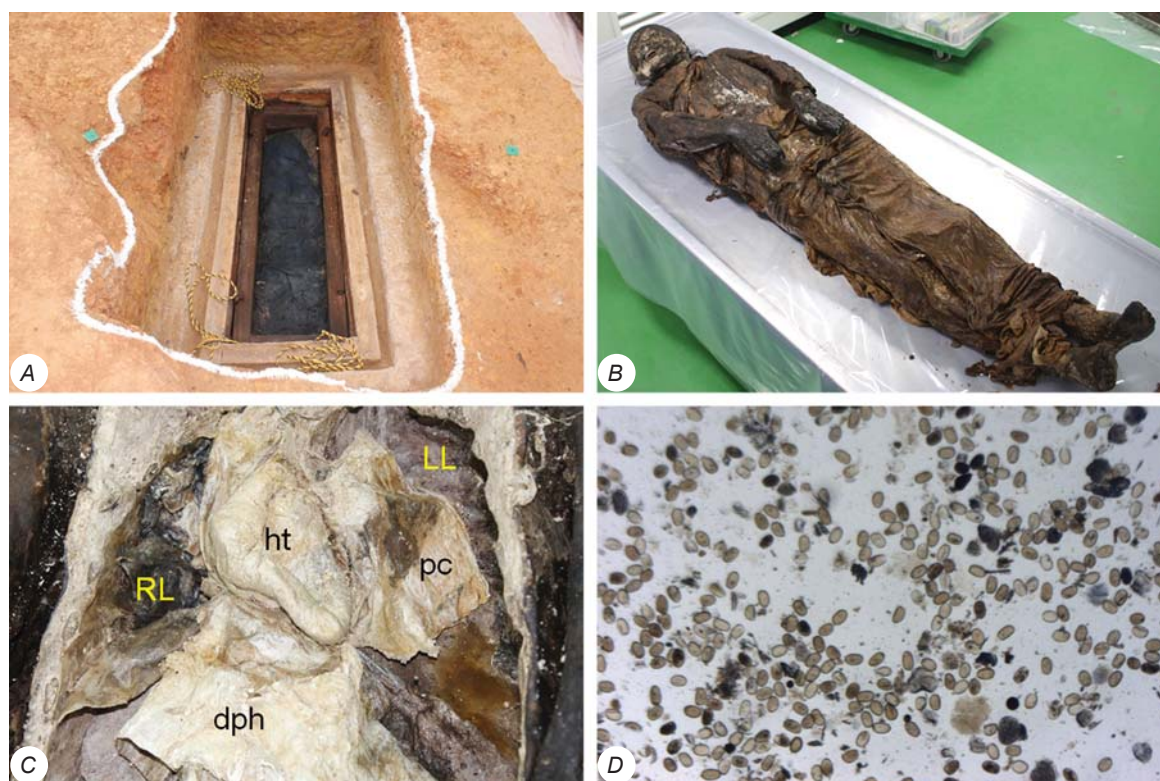


Fig. 1. The Joseon tomb where the well-preserved (Sacheon) mummy and artifacts such as clothing and documents etc. were discovered in 2011 (A); perfect preservation status of Korean mummy discovered at Hwasung (B); well-preserved internal organs remained within the body cavity of Hwasung mummy (C): LL – left lung, RL – right lung, ht – heart, pc – pericardium, dph – diaphragm; Ancient parasite *Paragonimus* eggs from (Yongin) mummy sample (D).

2014). Briefly, the signs of congenital or acquired diseases have been identified by gross anatomical examination, as well as histological and radiological investigations (Kim et al., 2014; Kim et al., 2015).

Further, microscopic or molecular techniques have been applied to the paleoparasitological analysis of ancient parasite eggs in Joseon mummy feces (Fig. 1, D). Our paleoparasitological studies over the past years have yielded data indispensable to the determination of parasitic infection patterns prevailing in historic Korean populations (Seo et al., 2014). When we compared the paleoparasitological data attained from Joseon mummies with South Korean national survey data to date, we were able to identify secular changes in the prevalence of parasitic infection throughout history (Seo et al., in press).

For the analysis of mummified remains and the pathogenic microbes or parasites infecting such individuals while they were living, ancient DNA (aDNA) analyses have been used. Since aDNA in the brain is much better preserved than in other areas, that organ has been the preferred resource for genetic analysis in Korean mummy studies (Oh et al., 2013). In the case of pathogen aDNA meanwhile, remarkable findings have been reported from ancient parasite eggs remaining inside

Joseon mummy-feces (Seo et al., 2014). In fact, these results have proved academically significant to Korean researchers, who have found them to be very useful for reconstruction of pre-modern Korean peoples' physical and pathological traits (Song, Shin, 2014).

How did mummification occur inside Joseon tombs?

Since the actual mechanism of mummification in Korea has yet to be fully elucidated, it is difficult to subsume the Joseon mummy into any category of mummies discovered worldwide. As far as we know, there were no specific embalming techniques employed in Korea; therefore we rule out the possibility that Joseon mummies were artificially formed (Kim et al., 2006). Considering especially that natural conditions in Korea are actually unsuitable for mummification, the Joseon mummy definitely does not belong to any category of natural mummification (e.g. dry land or permafrost zone) reported worldwide (Shin et al., 2003).

In this connection, Korean scholars speculate that the Joseon mummy was not formed by any known

simple mechanism, but rather under a very unique condition not commonly seen in other countries. Actually, Joseon mummies have been found exclusively in graves of a unique structure (*Hoegwakmyo*). Inside such a grave, the coffin is completely sealed by a wall of lime-soil mixture (Shin et al., 2003). We therefore considered the *Hoegwakmyo* tomb's unique structure with lime-soil-mixture barrier as an explanation for mummification. Nevertheless, the scientific evidence has been inconclusive. In an effort to answer this question definitively, a series of experiments have been recently performed using laboratory animals (rats) and miniature *Hoegwakmyo* tombs (Oh, Shin, 2014).

Temperature rising by exothermic reaction

In those experiments (Ibid.), a lime-soil mixture (lime : fine sand : yellow soil = 3 : 1 : 1) was filled into the space between the grave and the rat-containing coffin, as well as spread upon the coffin lid (Fig. 2, A). After a certain period of time, the lime-soil mixture hardened, thus forming a coffin-surrounding wall (Fig. 2, B). A second, wall-less miniature coffin was used as a negative control (Ibid.).

After enough time had passed, we found that the rats inside the miniature *Hoegwakmyo*-mimicking tombs were completely mummified (Fig. 2, C). The mummified tissues had maintained perfect morphologies with only minor taphonomic changes. Moreover, as no mummified rats were found in the negative control tombs, the presence of the coffin-surrounding lime-soil-mixture wall seemed highly correlated to mummification (Ibid.).

Next, in this study, we measured a temperature-change inside the *Hoegwakmyo* tombs. As is well known, quicklime (calcium oxide)'s contact with moisture induces an exothermic reaction. Likewise, when the lime-soil mixture of the *Hoegwakmyo* tomb meets moisture, heat could be generated. Considering that all species of bacteria can be sterilized by 100 °C heating for 90 minutes (atmospheric pressure) (Ananthanarayan, Paniker, 2006), the high heat maintained by the lime-soil-mixture wall over the course of a sufficient time period might have contributed to a condition of bacterial sterilization inside the *Hoegwakmyo* coffin.

To confirm the validity of our hypothesis, we conducted an additional experiment in this study, using the same animal model. We formed the lime-soil mixture around the coffin, and then determined the extent to which the temperature rose and how long it was sustained. To measure the temperature inside the coffins, a digital thermometer (KTH300 model, KIMO, France) was installed in the lid (Fig. 2, D). The temperature was measured over the course of 4 hours at 10-minute intervals. The treatment of animals during our experiments followed *The Guide for the Care and Use of Laboratory Animals*

(Guide..., 1985). The Institutional Animal Care and Use Committee (IACUC) of Seoul National University also approved this study (SNU-100806-2).

The results were astonishing. We observed a very strong heat generated by the lime-soil-mixture wall. During the experiments (n=10), the average temperature inside the lime-soil-mixture-walled coffin was sustained at 130.8 ± 23.5 °C for 141.0 ± 64.7 minutes (Fig. 2, E). Theoretically, this high temperature is enough to kill nearly all of microbes that might be present inside such coffins.

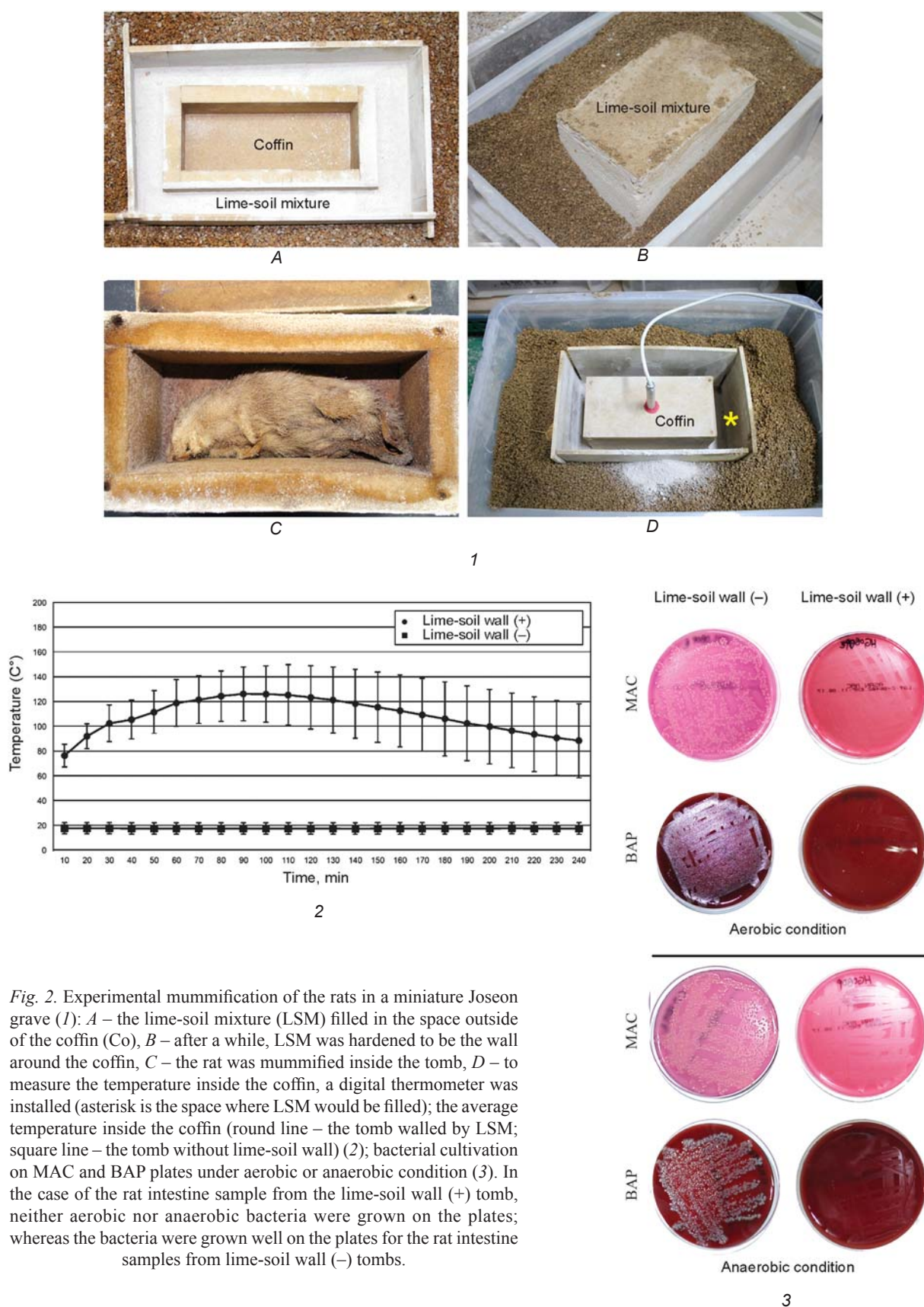
Indeed, the microorganisms present in the human body can grow rapidly after death, which is the main factor inducing decomposition (Gill-King, 2000). We thus believe that such a high and long-sustained temperature contributed to the prevention of post-mortem bacterial-induced decomposition inside Joseon tombs. We conducted another experiment to ascertain if microorganisms in a mummy could actually be sterilized by the lime-soil-mixture wall's exothermic reaction.

Bacterial culture on agar plates

Briefly, we cultured samples obtained by autopsy from the intestines of adult Sprague-Dawley rats (n=4), which had been placed inside the miniature coffins with or without a lime-soil-mixture wall. These samples, collected after 24 hours of burial, were spread on a MacConkey (MAC) or blood agar plate (BAP) (Asan Pharmaceutical, Seoul, Korea). MAC agar is generally used for primary selection of gram-negative bacilli. BAP supports all but the most fastidious clinically significant bacteria (Forbes et al., 2007).

After the bacteria had been incubated for 24 hours under the aerobic or anaerobic condition, we observed the results. In the case of the rat intestine samples obtained from the miniature *Hoegwakmyo*-mimicking tomb (with lime-soil-mixture barrier), neither aerobic nor anaerobic bacteria were cultured on MAC or BAP (Fig. 2, I, F). Meanwhile, the sample from the grave without any lime-soil-mixture wall showed bacteria growing well on the same plates. This means that the strong heat generated by the lime-soil-mixture wall sterilized the microbes, thus making possible mummification inside of the tomb much more likely.

Our experiments were very meaningful in estimating the mummification mechanism inside of Joseon tombs. However, as the difference in the sizes of the miniature- and actual tombs was so huge, a query was raised as to whether the same outcome could be reproduced in an experiment with a larger-sized animal. We thus repeated our experiment with New Zealand White Rabbits (n=6, average weight=2.6 kg, Samtako Bio Korea Co., Ltd., Korea).



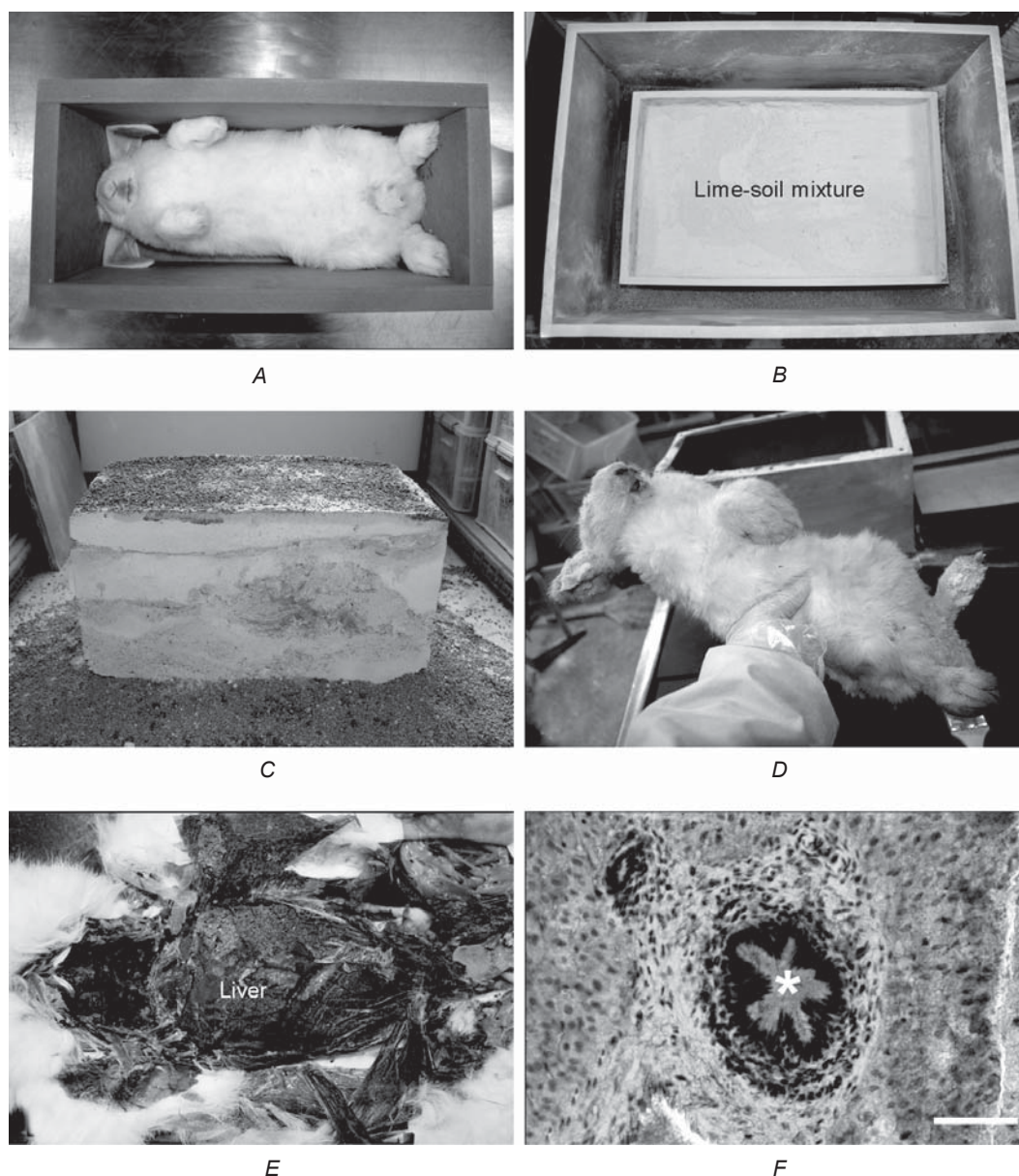


Fig. 3. Mummification of the rabbits in the miniature Joseon tomb. Rabbit were placed inside the miniature coffin (A); lime-soil mixture (LSM) was filled around the coffin (B); the LSM wall made after enough time has passed (C); mummified rabbit placed inside the miniature Joseon tomb (D); well-preserved liver found in autopsy on the mummified rabbit (E); liver tissue histology of mummified rabbit (asterisk indicates the portal vein; scale bar = 100 mm) (F).

In our anatomical and histological analysis, we saw that the rabbit's mummification also occurred in the miniature Joseon tomb with lime-soil mixture wall (Fig. 3, A–D). Although the miniature tombs used at this time were much larger than those of rat model experiments, our study exhibited perfect preservation status of the mummified rabbit tissues from the miniature Joseon tombs, while the same phenomenon was not observed in the cases without the lime-soil mixture walls (Figs. 3, E, F). We know that the same mummification

could be reproduced regardless of the sizes of miniature Joseon graves and experimental animals used.

Conclusions

By a series of animal experiments, our hypothesis on the role of the lime-soil-mixture barrier in the mechanism of mummification inside Joseon tombs was demonstrably proven. This discovery is really important for estimating

the mechanism of mummification inside the *Hoegwakmyo* tombs of Joseon dynasty.

Actually, there were arguments for a long time about the causes of mummification inside the Joseon tombs. The Korean archaeologists suspected that the mummification might have been caused by the presence of lime-soil-mixture barriers that completely sealed the Joseon tombs. No matter how persuasive, what they have speculated amounts only to a simple presumption. To strengthen the hypothesis, the actual process of mummification inside the *Hoegwakmyo* tombs must be proven by well-designed archaeological experiments, possibly using miniature grave-models.

In this study, we successfully showed that the mummification occurring inside the miniature Joseon tombs seems to have been influenced by the exothermic reaction of the lime-soil mixture in contact with moisture. We also exhibited that the mummification of the *Hoegwakmyo* tombs was likely to have been induced by the bacterial sterilization of the same exothermic reaction. Although this study can confirm the archaeologists' earlier guesses about the mechanism of mummification in Joseon tombs, it is still difficult to be sure that the same phenomenon of mummification by exothermic reaction will actually occur in actual-sized *Hoegwakmyo* tombs. An answer to this question will have to await more archaeological experiments in forthcoming days.

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