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Paleogenetic Study of Ancient DNA Suggestive of X-Linked Acrogigantism

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Dear Editor,

Pituitary gigantism is caused by chronic growth hormone (GH) hypersecretion by a pituitary lesion before epiphyseal fusion. Genetic causes have been identified in nearly 50% of patients with pituitary gigantism, with germline mutations in the *AIP* gene being the most frequent cause (Rostomyan *et al.* 2015). Recently, a new form of pituitary gigantism, X-linked acrogigantism (X-LAG), was described (Trivellin *et al.* 2014). X-LAG is due to chromosome Xq26.3 duplication and *GPR101* is the disease-associated gene (Trivellin *et al.* 2014; Iacovazzo *et al.* 2016). X-LAG is characterized by of mixed GH/prolactin-secreting pituitary macroadenomas and/or hyperplasia in early childhood (Beckers *et al.* 2015). X-LAG typically occurs sporadically in females, but somatic mosaicism also occurs in males; familial mother-to-son transmission of the Xq26.3 duplication has been reported in three familial isolated pituitary adenoma families (Trivellin *et al.* 2014; Daly *et al.* 2016; Gordon *et al.* 2016; Iacovazzo *et al.* 2016). The clinical presentation of X-LAG syndrome differs from other genetic forms of pituitary gigantism (Rostomyan *et al.* 2015) and many well-known historical cases of gigantism share the clinical characteristics of X-LAG syndrome (Beckers *et al.* 2015; Rostomyan *et al.* 2015). If untreated during childhood X-LAG leads to established extreme gigantism (>1.9 meters) before puberty (Daly *et al.* 2016).

We studied a historical case of severe acro-gigantism. The subject, J.K., was born in 1872 in Reutlingen, in what is now Baden-Württemberg, Germany. His parents and brother were of normal size. It was reported by his doctor that J.K. had always been "very large" and was reputed to have a huge appetite; he measured 1.94 meters at the age of 14 and never stopped growing thereafter (Launois & Roy 1904). In contemporary Würtemberg the average adult male height was only 164 cm. By the 1890's he was exhibiting himself as *Giant Constantine/Le Geant Constantin* (Figure 1A). In 1898 he was 259 cm in height (8 feet 6 inches) and weighted 168 kilograms (370 pounds). He fell ill while in the Walloon region of Belgium and was hospitalized on November 15, 1901, at the Hôpital Civil in Mons, Belgium with a fever (39.3ºC) due to severe lower limb gangrene. Hospital records show his height as 256 cm and weight of 180 kg. He improved initially after an amputation of the right leg, but the following year he fell and the other leg was amputated below the knee. He developed post-operative septicemia and died on March 30, 1902. At autopsy the pituitary was grossly enlarged to the size of "a large walnut" (Launois & Roy 1904). The sella turcica was also greatly enlarged, so much so that it was remarked that "*after removing the cerebral hemispheres and the cerebellum the sella was so broad and deep that it brought to mind two juxtaposed spinal canals*" (Launois & Roy 1904) (Figure 1B, C). The long bones and extremities were elongated and the proximal humeral epiphyses remained unfused (Launois & Roy 1904). Concomitant hypogonadism (testicular atrophy) was present on examination and post-mortem. Current forensic analysis of the

skeleton demonstrates bleaching of bones consistent with a reported preservation by prolonged boiling.

Given the clinical history of early onset acrogigantism, an underlying genetic cause was thought to be likely. DNA extraction from teeth was unreliable as the skull was edentulous when originally photographed in 1904 (Launois & Roy 1904); subsequently teeth were added to the skull but they could not be confirmed as coming from the subject himself. The skeleton was fragile after preservation by prolonged boiling and DNA extraction from metatarsal and the femur were unsuccessful. Based on results obtained from ancient skeletal remains, tissue from the cochlea was obtained via the petrous temporal bone (Pinhasi *et al.* 2015) as reported in Supplemental Materials. His history of early-onset, severe pituitary gigantism led us to suspect X-LAG (Trivellin *et al.* 2014; Daly *et al.* 2016).

The DNA sample was assayed using a ddPCR technique as previously described (Daly *et al.* 2016). Briefly, the ddPCR compared copy number variations (CNV) at the *GPR101* gene as compared with *ZIC3*, a gene that is not duplicated in X-LAG syndrome. Daly et al recently showed this method was reliable for both confirming the results of known Xq26.3 duplication carriers and non-carriers, while also identifying duplication of *GPR101* during screening of previously undiagnosed cases of X-LAG syndrome; the false positive rate in the acro-gigantism population was low (1/64 cases was borderline above the CNV minimal and maximal thresholds for duplication) (Daly *et al.* 2016). The study was approved by the Natural History Museum of Mons and genetic studies regarding causes of gigantism and endocrine tumors was conducted under approval of the Ethics Committee of the Centre Hospitalier Universitaire de Liège, Belgium.

We extracted DNA from cochlear core powder, then sequenced and post-processed it on a custom bioinformatics platform for ancient DNA. The DNA had deamination patterns consistent with that of a nearly 100-year-old sample. No pathological variants in *AIP* and other gigantism-associated genes (e.g. *MEN1*) were noted on obtained DNA read sequences. DNA was insufficient for array comparative genomic hybridization studies. The subject's DNA exceeded the statistical thresholds for *GPR101* duplication (copy number variation (CNV) value: 3.49 vs. >2.0; Poisson CNV minimum value: 3.28 vs. >2.0), indicating X-LAG as a likely cause of his severe pituitary acrogigantism.

The increased copy number for *GPR101* strongly suggests that J.K. suffered from X-LAG syndrome. The clinical and tumoral characteristics of X-LAG are supportive of this proposed diagnosis. To achieve a height of 194 cm at the age of 14 in the 1870's required a significant period of uninterrupted overgrowth. Apart from X-LAG, few other conditions are associated with early childhood-onset pituitary gigantism. The skeleton had no evidence of McCune-Albright syndrome and *AIP* mutation-associated gigantism typically begins in mid-adolescence (Rostomyan *et al.* 2015). X-LAG syndrome is associated typically with mixed GH and prolactin

secreting pituitary adenomas (with variable hyperplasia); tumors are usually macroadenomas and can be large and invasive as in the subject's case (Trivellin *et al.* 2014; Beckers *et al.* 2015). Testicular atrophy was also present in the current case that indicates significant effects of the pituitary tumor on gonadal function. This would have kept the epiphyses thereby contributing to the final height of 259 cm. His proximal humeral epiphyses never fused, and his femoral epiphyses only fused late in his life, according to his autopsy accounts (Launois & Roy 1904). Hypogonadism could have been caused by tumor impingement upon gonadotropes, compounded by hyperprolactinemia which is common in X-LAG syndrome (Trivellin *et al.* 2014; Beckers *et al.* 2015). Few adult cases of X-LAG have been characterized, so the prevalence of hypogonadism due to tumor impingement is not known, but is a logical effect of a large tumor mass.

Advances in sequencing technologies, DNA extraction methods, and bioinformatic analysis have allowed researchers to overcome challenges such as DNA authentication, contamination from modern and ancient sources, and have provided access to genetic material from samples thousands of years old and originating in tropical and desert environments (Pinhasi *et al.* 2015; Skoglund *et al.* 2016). These extreme conditions are not optimal to the preservation of DNA. DNA has been retrieved from skeletal remains of other giants using techniques that have relied on DNA recovery from molar teeth. In a recent historic gigantism case no *AIP* mutation was found; X-LAG was not studied but ddPCR specific to *GPR101* and *ZIC3* similar to that reported here could be informative (Radian *et al.* 2016). As no DNA could be derived from teeth or other bony sites we utilized the novel approach of retrieving cochlear DNA from within the petrous temporal bone as developed and validated recently in population studies (Pinhasi *et al.* 2015; Skoglund *et al.* 2016). Even in skeletal samples that are preserved by suboptimal means during preservation, retrieval of DNA and strongly supportive information that is consistent with the patient's clinical history can be obtained. This approach could be applied more generally to other possible genetic disorders that are evident on skeletal remains. Also, studies similar to this case could address the utility of other approaches to CNV analysis such as quantitative PCR on non-amplified genomic material. The increasing number of ancient genomes that have been retrieved from phenotypically normal skeletons could provide a useful database of normal ancient DNA features and highlight the interference by environmental factors and age on the analysis and assessment of potentially disease-related variants.

Valuable medical information can be gained from the genetic study of skeletal remains. While J.K. died before the era of pituitary tumor treatment, pituitary gigantism remains a difficult to treat condition today (Beckers *et al.* 2015; Rostomyan *et al.* 2015). Better understanding of the natural disease history and potential genetic causes of historical giants should reinforce the need for early effective disease control.

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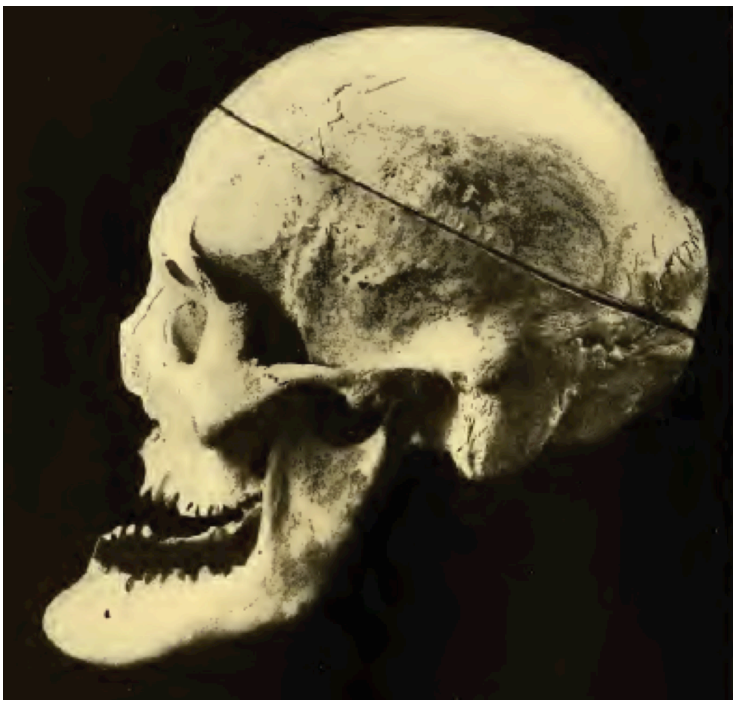

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