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## An Encouraging Progress Report on the Treatment of Progeria and Its Implications for Atherogenesis

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There are no known human genetic syndromes that faithfully accelerate all of the common phenotypes associated with aging, but there are several striking disorders with multiple features (segmental progeroid syndromes). The suffix-oid is conceptually important, because it leaves open the possibility that the underlying mechanisms may differ to some extent from what is considered the usual pathogenesis. Two canonical examples are the Werner syndrome and the Hutchinson-Gilford Progeria Syndrome (HGPS). In both disorders, atherosclerosis is a particularly striking feature, causing the majority of deaths, usually via a myocardial infarction (although cancer is also a common cause of death in Werner syndrome, a later-onset disorder). Werner syndrome is an autosomal recessive disorder due to null mutations at a member of the RecQ family of DNA helicases and is associated with accelerated clonal senescence of somatic cells and genomic instability.<sup>1</sup> HGPS is caused by a specific class of autosomal dominant mutations in lamin A, a component of the nuclear membrane. The causative mutations result in the synthesis of large amounts of an alternatively spliced toxic isoform known as progerin<sup>2–4</sup>; it is thus a gain-of-function mutation.

During the maturation of prelamin A, a farnesyl group is added to a cysteine residue at the C terminus and subsequently removed by a proteolytic enzyme, Zmpste24, to produce mature lamin A. In progerin, the proteolytic site for Zmpste24 is deleted because of a cryptic splice site generated by the mutation.<sup>2,3</sup> A mouse model expressing the nonfarnesylated progerin exhibited near-normal phenotypes, supporting the interpretation that progerin toxicity is mediated by the farnesyl moiety.<sup>5</sup> The severities of the disease correlate with the amount of progerin, a function of the activity of the cryptic splice site.<sup>6</sup> The size of the deletion also

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contributes to the severity of the phenotype. The majority of classical early-onset forms of HGPS result from a 50-amino-acid deletion. Attenuated forms of the disease have been associated with alternative deletions that lead to lesser amounts of the progerin isoform.<sup>7,8</sup>

Of major biomedical interest have been reports that small amounts of progerin can be detected in human tissues, including human arteries, and that these amounts increase with age.<sup>9,10</sup> These observations now raise the important question of the extent to which progerin contributes to human atherogenesis.

In this issue of *Circulation*, Gordon et al<sup>11</sup> describe small but robust increases in the survival of HGPS patients following treatments that interfere with the posttranslational farnesylation of lamin A proteins. Remarkably, given the extreme rarity of this disorder,<sup>12</sup> this team, assisted by the efforts of a highly successful Progeria Research Foundation (<http://www.progeriaresearch.org/>), managed to assemble a cohort of 161 untreated control HGPS patients and 43 HGPS patients who were treated with either a single farnesyltransferase inhibitor, lonafarnib, or 2 additional agents that also inhibited farnesylation: a bisphosphonate (zoledronate), which inhibits the synthesis of farnesyl-pyrophosphate, and a statin (pravastatin), which inhibits 3-hydroxy-3-methylglutaryl coenzyme A reductase (see Figure 1<sup>11</sup>).

Recruitment of control disease subjects did not require genotyping, although some are listed in Table III in the online-only Data Supplement.<sup>11</sup> In contrast to the experience of our International Registry of Werner Syndrome, however, in which we could only provide a molecular diagnosis of  $\approx 80\%$  of clinical diagnoses, molecular confirmations of clinically diagnosed HGPS are much more robust, probably well in excess of 95%. Moreover, all treated subjects were in fact genotyped, some of whom had *LMNA* mutations that resulted in lower levels of progerin (see Table V in the online-only Data Supplement<sup>11</sup>).

It is important to note that the treated group included patients with any duration of treatment, either during a previous 2-year trial of farnesyltransferase inhibitor monotherapy or during an ongoing 3.5-year trial of combination treatment. Given that feature of the study, the Kaplan-Meier curves of Figure 2B<sup>11</sup> are even more impressive – 21/43 deaths in the untreated group versus 5/42 deaths in the treated group during the approximately 5-year period of this study.

The authors suggest that the increased longevity of the treated HGPS patients was due to a reduction of cardiovascular pathology, a very plausible hypothesis. Investigators engaged in survival studies must always keep in mind, however, the possibility that any intervention with the potential to induce dietary restriction might have a more general effect on the pathophysiology of aging.<sup>13</sup> This is extraordinarily unlikely in the present case, however, given the precise target of the interventional agents and the fact that there was no evidence of weight loss in a previous preliminary trial of monotherapy.<sup>14</sup>

The authors point out that the present data now provide the best available baseline data of HGPS survival for use by interventional trials with other agents. Among these future potential interventions is research that uses a mouse model of HGPS to evaluate phenotypic improvements via the targeting of an enzyme, isoprenylcysteine carboxyl methyltransferase,

which is responsible for the methylation of isoprenylcysteine.<sup>15</sup> After farnesylation of prelamin A and progerin, farnesylcysteine is methylated by isoprenylcysteine carboxyl methyltransferase before cleavage by Zmpste24. Zmpste24-deficient mice expressing hypomorphic isoprenylcysteine carboxyl methyltransferase showed striking ameliorations of HGPS-like phenotypes and upregulation of mammalian target of rapamycin (mTOR) signaling.<sup>15</sup> In contrast to those mTOR results, however, Cao et al<sup>16</sup> showed that long-term treatment of HGPS cells with the mTOR inhibitor, rapamycin, facilitated the autophagic clearance of progerin and reversed cellular HPGS phenotypes. Therefore, mTOR inhibitors could prove to be useful in the treatment of age-related disorders, including the treatment of Werner syndrome.<sup>17</sup> Since the advent of drug-eluting coronary stents that deliver sirolimus or everolimus to prevent restenosis, the use of systemic mTOR inhibitors has been approved by the Food and Drug Administration for the treatment of renal and brain manifestations of the genetic condition, tuberous sclerosis, and for the treatment of HER2-negative breast cancer, pancreatic neuroendocrine tumors, and advanced renal cell carcinoma, as well. There is also much current interest in the use of rapalogs, chemical agents that may have fewer side effects, for example, on immune suppression.<sup>18</sup> Finally, there are reports of the use of RNAi against progerin mRNA that showed improvements of cellular HGPS phenotypes.<sup>19,20</sup> Such gene therapy, however, may not be practical at this point because of the limitations of delivery systems.

Returning to the consideration of the most biomedically significant HGPS phenotype, atherosclerosis, 2 issues remain to be resolved. The first is the histopathologic observations of apparent phenotypic discordances with atherosclerosis as it usually occurs. Of particular interest are the unusually extensive periarterial adventitial fibrosis and the involvement of vascular smooth muscle alterations.<sup>9</sup> The latter issue has been addressed in part by in vitro studies indicating that aging normal vascular smooth muscle cells reiterate the aging phenotype of HGPS fibroblasts in culture and that this process of cell senescence is accelerated by the accumulation of prelamin A.<sup>21</sup> The former observation will require more research, however.

The second issue is the need for more robust animal models of HGPS that include atherosclerosis. To the best of our knowledge, atherosclerosis has yet to be demonstrated in any of the several published mouse models of HGPS. The use of alternative animal models, such as the miniature pig, would be highly desirable.<sup>22</sup>

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We dedicate this editorial to the memory of Sam Berns, a highly intelligent and heroic HGPS patient and the son of the first author of the article addressed by this editorial. For one of Sam's inspirational addresses, the reader is referred to the TED talk he presented shortly after his 17th birthday: <https://www.youtube.com/watch?v=36m1otM05g>.

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