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"By the end of the next decade, Russia must with confidence join the Club of countries where life expectancy exceeds 80 years..."

from the Presidential Address to the Federal Assembly of the Russian Federation, March 1, 2018

Where Does the Preston Curve Lead Us?

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Abstract—World Bank and Russian Federal State Statistics Service data were used to analyze cross-country correlations between life expectancy (LE) and per capita gross domestic product (GDP). The trends detected upon comparisons across different countries (the Preston curve) or regions of the Russian Federation (RF) in 2015 were compared. In addition, the correlations between the same parameters related to different years, from 1960 to 2015, were examined in each of several selected countries representing the upper and lower extremes of GDP and LE. The same has been done with LE vs. per capita health care spending (HCS). In all cases, the points related to the RF are located significantly lower than the respective regression lines (Preston curves) built based on all points. The LE vs. GDP and LE vs. HCS plots and their extrapolations constructed based on data related to different years in the same country run markedly lower for the RF as compared with other countries, including Tajikistan and the Republic of Congo. At the same time, the ratio of GDP and HCS has been shown to be the same throughout all years and all countries. Taken together, these observations suggest that the effectiveness of investing available resources in LE, i.e., in the quality of human life, is markedly lower in RF as compared not only with Finland and Japan, where GDP and HCS are several times greater but also with Congo and Tajikistan, where these parameters are several times smaller than in the RF. This means that in the RF, it is impossible to increase LE up to 80 years, which has been declared a national priority, merely by increasing GDP and HCS. Identification of the factors responsible for the above disproportions is beyond the scope of the present paper. However, the mere awareness of their existence is essential as an incentive to take special efforts aimed at the identification and neutralization of these factors.

Keywords: life expectancy, gross domestic product, health care spending, Preston curve
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INTRODUCTION

Since March 1, 2018, one of the national priorities of the Russian Federation (RF) has been to join the "80+ Club," which refers to the group of countries where life expectancy at birth exceeds 80 years. In this regard, it is necessary to understand how the participants of this "Club" got where we all will be if everything goes as planned. This is the only way to foresee possible obstacles on this path and ways to overcome them, considering the fact that life expectancy of *Homo sapiens* is defined not only by economy and politics, but also by the biological aspect of the species.

In the meantime, all participants of the 80+ Club have got there by following a curve—the Preston curve—named after the author of the paper [22] where this curve was first presented. Essentially, it is a trend identified by a comparison of life expectancy and per capita gross domestic product (GDP) in different countries. Below, the GDP will imply a specific value per capita per year. Figure 1 shows the relationship between GDP and life expectancy as of 2015.

The Preston curve reflects at least three circumstances. (1) Life expectancy increases as the availability of life support resources grows. (2) Life expectancy cannot grow infinitely despite the amount of resources spent; therefore, as the GDP grows, the increase in life expectancy slows down. (3) The scatter of points around the Preston curve suggests that life expectancy notably depends not only on the availability of life support resources but also on the conditions of their expenditure; aside from environmental conditions, the following is taken into consideration: distribution of resources between different budget items (healthcare, defense, development investments, etc.) and dif-

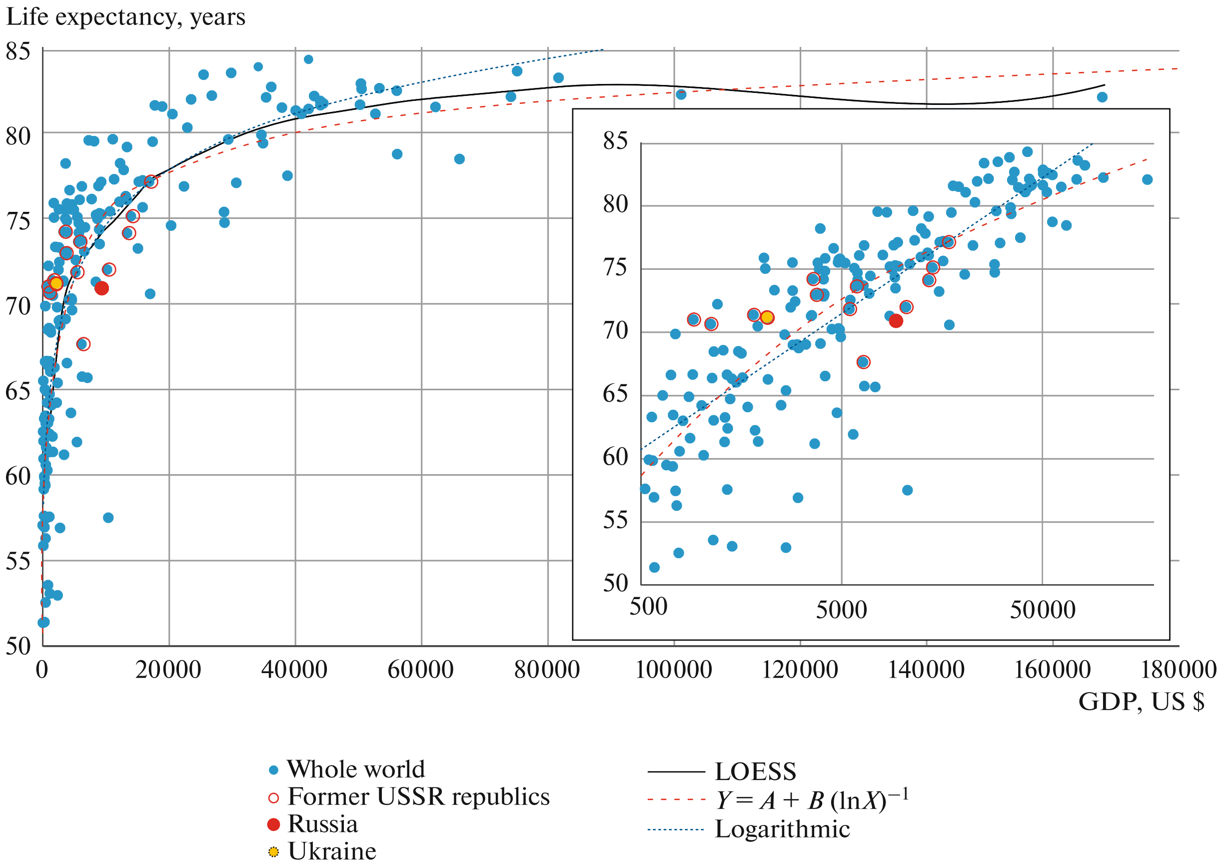

Fig. 1. Correlation between per capita GDP (US $) and life expectancy (years) in different countries based on 2015 data available at World Bank website (https://data.worldbank.org/indicator). The Preston curve proper is the regression of life expectancy on GDP. In the original article by Preston [22], the regression is approximated with a logistic function $Y = A/(1 + e^{f(X)})$ in order to account for the existence of life expectancy limit. Preston defined this limit as 80 years ($A = 80$). Later on, the points in the coordinates (GDP, life expectancy) have been being often approximated with a logarithmic curve (most likely because this function is available in Excel), although it is obvious that this curve increases infinitely. In terms of pure approximation with possibly simple equations having no more than two parameters, the best correspondence to data points is achieved with functions like $f(Y) = A + B/\ln X$, where $f(Y)$ can be Y^2, Y^{-1}, $Y^{1/2}$, or $\ln Y$. Interestingly, with such functions, life expectancy at $X \to \infty$ asymptotically approaches the limit of 110–120 years, which corresponds to estimates based on other considerations [5, 7, 18, 19]. Of the three curves in Fig. 1, one is built using locally estimated scatterplot smoothing (LOESS). This approach makes it possible to see without bias that, in countries where the GDP is about 30000 US $, further increase in GDP does not result in an increase in life expectancy, even in Luxemburg and Lichtenstein (120000 and 180000 US $, respectively). The second curve represents the common logarithmic trend. The third is an approximation with the function Life Expectancy = $A + B/\ln$GDP. In this case, the limit of life expectancy at GDP $\to \infty$ is 110 years (95% confidence interval is 107; 114). The insert on the right shows the same in a semilogarithmic scale.

ferent population groups (wealth inequality, urban/rural etc.) [2, 4, 22, 24], the contribution of the mining industry to economy [6], national lifestyle characteristics [9], and many other aspects, which may contribute variably depending on circumstances. In particular, it is worth mentioning that, in virtually all 80+ Club members as of 2015, GDP exceeds 20000 US $ (only in Greece and Portugal GDP is lower but still exceeds 19500 US $) and that several countries that are very close to joining the Club have a GDP comparable to the average Russian value (9930 US $). The countries are (US $; years): Lebanon (8452; 79.5), Cuba (7600; 79.55), and Costa Rica (11406; 79.6). That is a condition: all of these countries are either Mediterranean or Caribbean. Climate is not cancelled. The successful Finland joined the 80+ Club when GDP exceeded 51000 US $ (see below).

Although such conclusions may seem banal, the Preston's paper of 1975 [22] has been cited worldwide about fifteen hundred times. In the RF, the first time was in 2012 [9], when the peculiar position of Russia relative to the Preston curve as of 2010 was brought to attention. This position was at the bottom of data point distribution around the curve segment corresponding to the Russian GDP and far lower than that of many other countries in which GDP does not reach even a

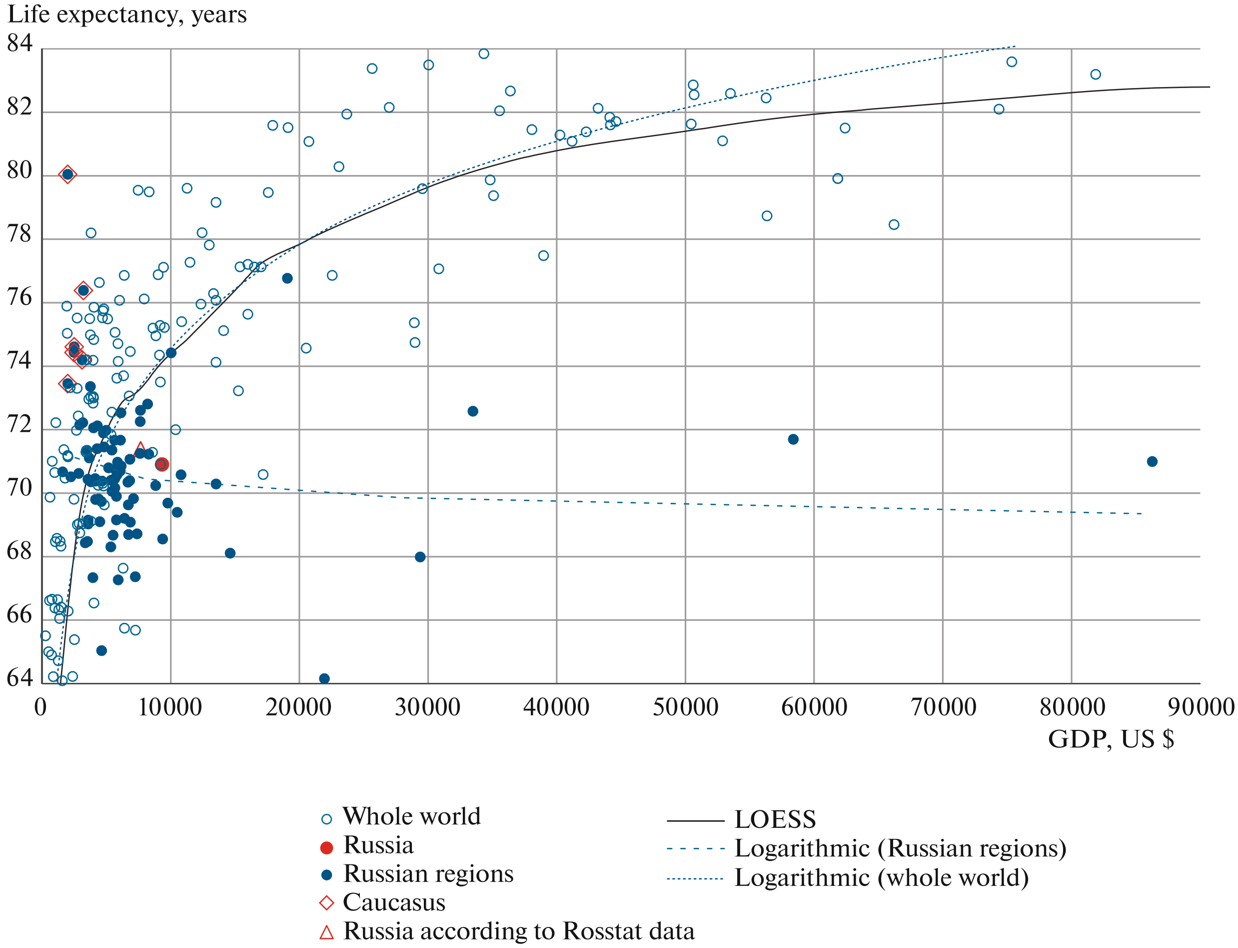

Fig. 2. Preston curve as a dotted line by countries of the world, including Russia as a whole. The dashed line represents Russia by regions. Diamonds highlight the republics of the Northern Caucasus.

half of the Russian value. Figure 1 shows that the situation did not significantly improve 5 years after. In 2013, when GDP peaked in the RF (1.5 times higher than in 2010, as well as in 2015 when GDP returned to the value of 2010), life expectancy was about the same, 72 years. In this regard, Suriname is close to the RF. Of the countries in which GDP is slightly higher than in Russia, life expectancy is lower only in Equatorial Guinea (10700; 57.5) and Trinidad and Tobago (17300; 70.6). The possible reasons of the anomalies represented by the two countries have been discussed earlier [9].

One of the factors of noncorrespondence between GDP and life expectancy may be the nonuniformity of GDP distribution by regions and/or different population strata. Since the increase in life expectancy does not depend linearly on GDP—it gradually slows down and virtually discontinues after GDP reaches 30000 US $ (Fig. 1)—it turns out that the more GDP increases where it is already high (so that further GDP growth leads to a relatively smaller increase in life expectancy than where GDP is lower and thus life expectancy depends on GDP more), the more significant will be the deceleration of increase in life expectancy in the population in general. Russia is very heterogeneous in both wealth and territory contexts. This is why it is of interest to determine how GDP and life expectancy are correlated across regions.

So far, data of this kind have been only published for China, where the comparison of provinces showed patterns generally corresponding to the Preston curve [24].

As usual, Russia does not fit into the general framework, as it may be inferred from data published by the Russian Federal State Statistics Service (Rosstat)[1] and converted from rubles into US $ under the exchange rate of the day of plotting of Fig. 1. The result is shown in Fig. 2, where the conformance of the relationship between life expectancy and GDP to the general Preston curve is absent as far as Russian regions are compared.

[1] http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/ru/statistics/publications/catalog/doc_1138623506156.

Table 1. The most abnormal regions of the Russian Federation in terms of the Preston curve

Region	GDP, US $	Life expectancy, years	Share of the total RF population, %	Proportion of the indigenous people, %
Khanty-Mansi Autonomous Okrug	33495	72.6	1.1	1.7
Yamalo-Nenets Autonomous Okrug	58389	71.7	0.4	6
Nenets Autonomous Okrug	86291	71.0	0.03	18
Sakhalin	29395	69.0	0.3	<1
Chukotka Autonomous Okrug	21950	64.2	0.03	25
Total	–	–	1.86	–
Ingushetia	2006	80.1	0.33	98
Dagestan	3223	76.4	2	91
Kabardino-Balkaria	2517	74.6	0.6	70
Karachay-Cherkessia	2486	74.4	0.3	69
North Ossetia	3131	74.2	0.5	70
Chechnya	2008	73.5	1	94
Total	–	–	4.73	–

On the right, the correspondence of GDP and life expectancy to the Preston curve is violated in the Russian regions where the GDP exceeds 20000 US $, so it would seem that this barrier to joining the 80+ Club has been already overcome there, albeit in a somewhat inadequate manner, 10 years by. These regions are listed at the top of Table 1.

Four of the top five anomalies are observed in national autonomous regions. GDP in both Nenets autonomous regions exceed the GDP in Sweden, where life expectancy is currently 86.2 years. Another anomaly is Sakhalin Island: its GDP is higher than, say, in Spain, but life expectancy is 15 years shorter. It would be reasonable to factor out these five anomalies.

On the left side there are the six Russian regions that feature the highest life expectancy (aside from Moscow and St. Petersburg) and, at the same time, the lowest GDP, which is even lower than that in the regions with the lowest life expectancy (Jewish Autonomous Region and Chukotka Autonomous Region), as well as the other ten where life expectancy is less than 70 years. All of the six regions are Northern Caucasus republics. Let us also factor out the anomalies at the bottom of Table 1.

Both groups of anomalies are represented by regions comprising only a small portion of the RF population. They do not set the tone, but they still spoil the picture.

Since almost all of the anomalies in the table are represented by national republics, autonomous regions, and oblasts, it makes sense to determine the situation in the Central Federal Region, which does not have those. Figure 3a shows that there are indeed significant positive correlations between GDP and life expectancy ($p < 0.0001$ and $p < 0.001$, respectively) regardless of the presence or absence of such a peculiar administrative object as Moscow in the analysis (the point for Moscow is outside of the 95% confidence interval). Figure 3b illustrates the situation in the Northwestern Federal Region (with the exception of Nenets Autonomous Region, which follows its own laws according to its position relative to the Preston curve). It is seen that there is a positive correlation between GDP and life expectancy in the Northwestern Federal Region, but it is not statistically significant. The same goes for the Urals, Siberia, and the Far East (except for the abnormal autonomous regions). The Volga region is outstanding (Fig. 3c) in that the correlation of GDP with life expectancy is negative, and if the territories defined by the national assignment are not considered, this trend becomes statistically significant ($p = 0.019$).

Representing the data obtained for each of the federal regions of Russia in the context of the global situation results in Fig. 4.

Figure 4 suggests the following. Even in the Central and Northwestern regions, the trends are lower than that related to the whole world; therefore, if we assume that life expectancy notably depends on GDP, then Russia will be able to join the 80+ Club only upon GDP amounting to 50000–60000 US $ (just like Finland, which is already there) instead of 20000. The situation in other Russian regions is not so favorable, especially in the Volga region, where it is just outrageous.

In the meantime, there are no countries in the 80+ Club with a GDP of less than 20000 US $ (except for Greece and Portugal—see above). On reaching this level, life expectancy in Russia will not exceed 78 years

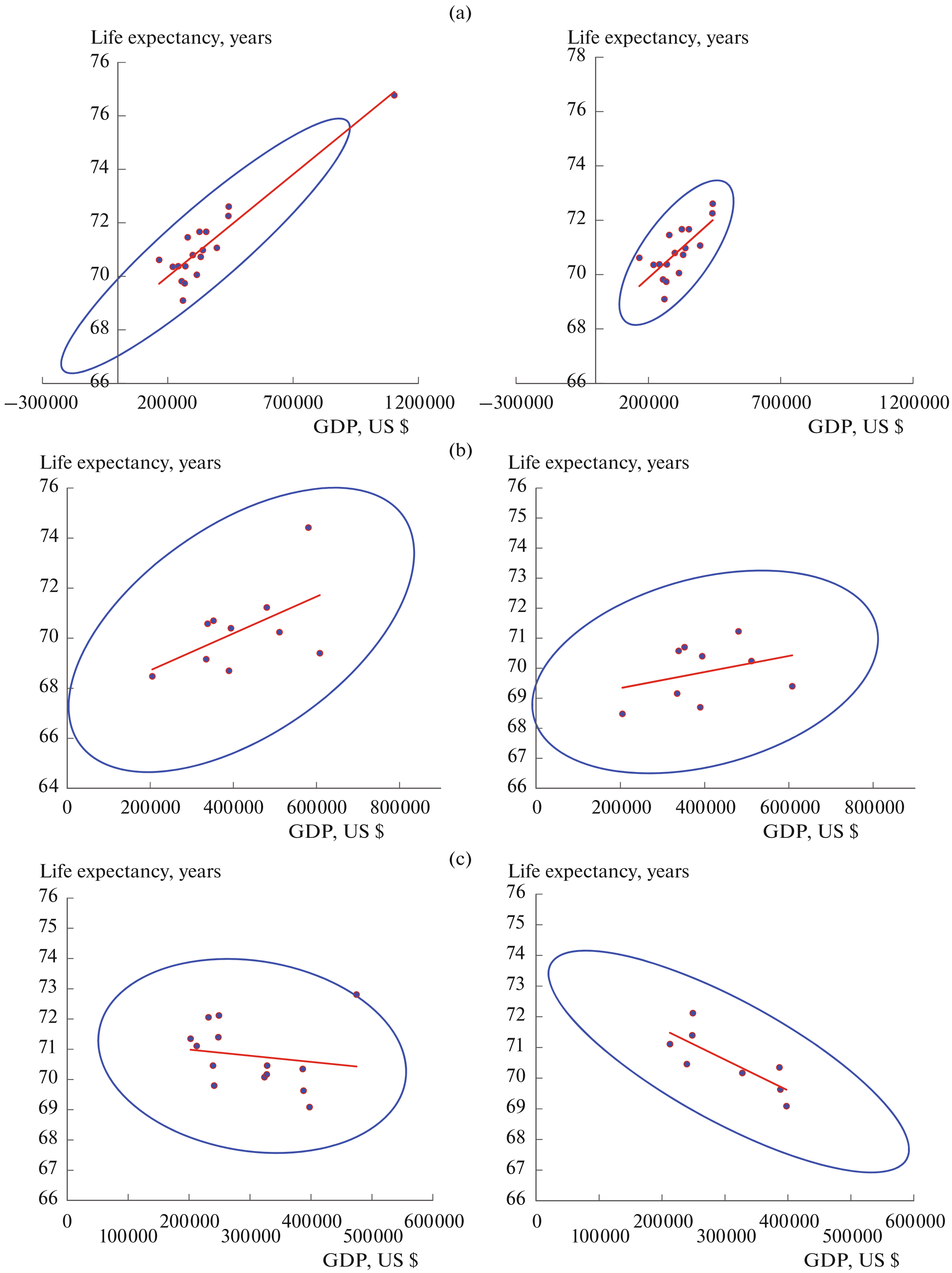

Fig. 3. Relationship between GDP and life expectancy in different Russian regions. Left column: Central Federal Region (a), Northwestern Federal Region (b), Volga Region (c). Right column: the same except Moscow, St. Petersburg, and national autonomous regions and republics. Straight lines represent linear trends. Ellipses are 95% confidence areas. The Rosstat data were treated with XlStat tools.

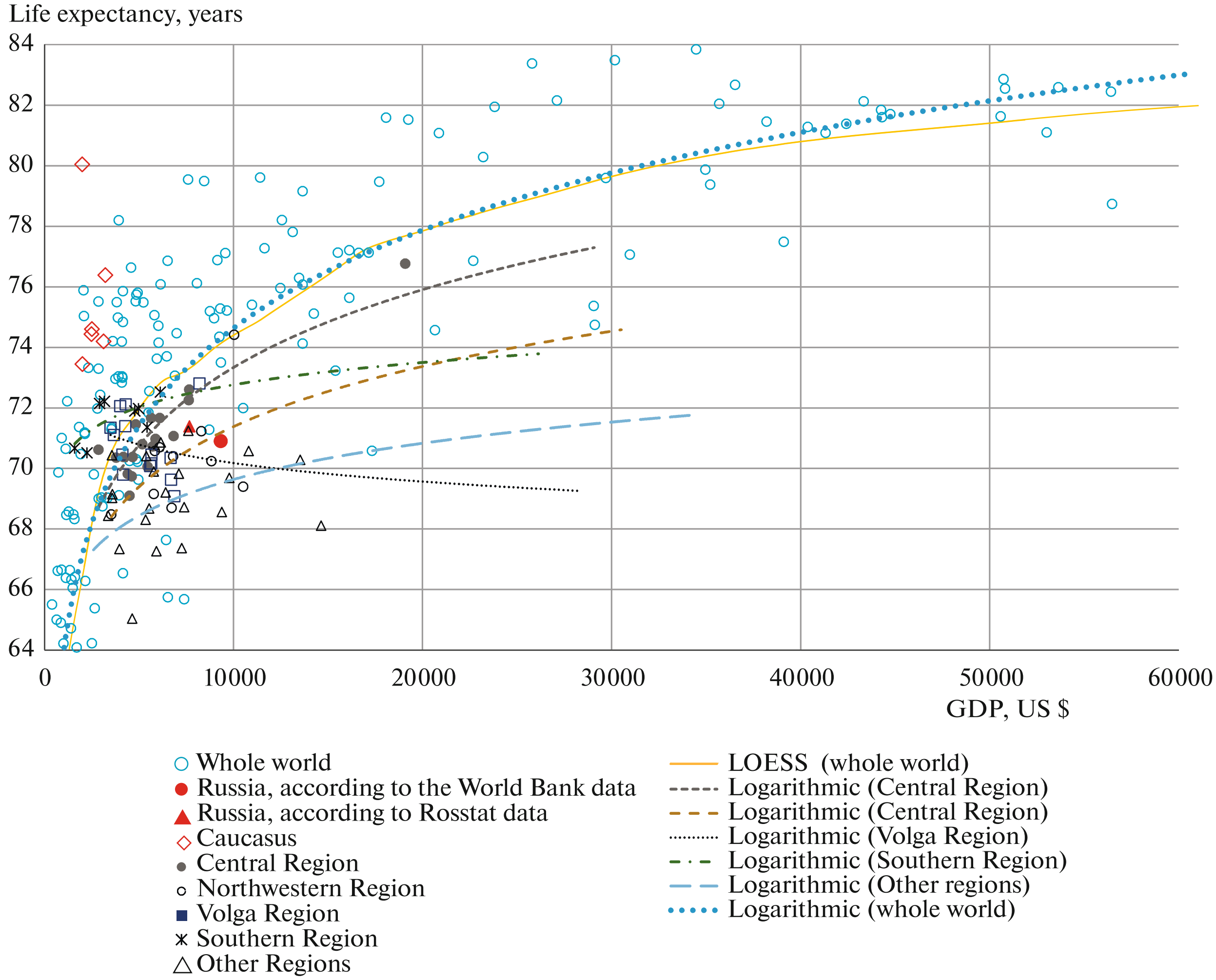

Fig. 4. Trends of the relationship between GDP and life expectancy in Russian regions in comparison with other countries of the world. Within the intervals shown in Fig. 3, the trends may be considered as linear; however, if they are extrapolated towards increased GDP, one cannot ignore their nonlinearity; therefore, the regional trends of Russia are represented with logarithmic curves, so as the global one is.

in Moscow, 76 years in the Northwest, and 72 years in other territories (except for the Northern Caucasus).

What is there to be done? Would it be acceptable to think that the nature of relationship between life expectancy and GDP is absolutely different here? This assumption is false according to Fig. 5, which shows the variants of the Preston curve constructed using different GDPs achieved in different years (1960–2015) in each country, instead of GDPs in different counties as of a particular year. It may be easily seen that, at any achieved GDP, life expectancy in Russia is 5 to 6 years shorter than in Finland and 10 years shorter than in Japan. The age of eighty years is not achievable at any GDP possible in the foreseeable future.

If we compare changes in GDP and life expectancy during radical socioeconomic reforms in 1989–2015 (Fig. 6), it may been seen that, although GDP and life expectancy change over time in a nonmonotonous manner, trends in their changes are unidirectional, even if changes are more pronounced for life expectancy.

Thus, life expectancy in Russia does depend on GDP; moreover, the dependence is stronger if the GDP is lower (as everywhere). Obviously, data on relationships between GDP and life expectancy, no matter how regular they are, suggest nothing regarding the dynamics of the GDP itself. Predictions for a period that is too long to allow for any computations and too short for the general trend to be manifested are not a topic for discussion in an article assumed to be scientific. One may only rely on the opinion of those who declare themselves to be experts in this area. Such opinions are not published in the peer-reviewed scientific literature. According to the most optimistic predictions found in the Internet upon queries like [GDP Russia 2030], the Russian GDP will not grow by more

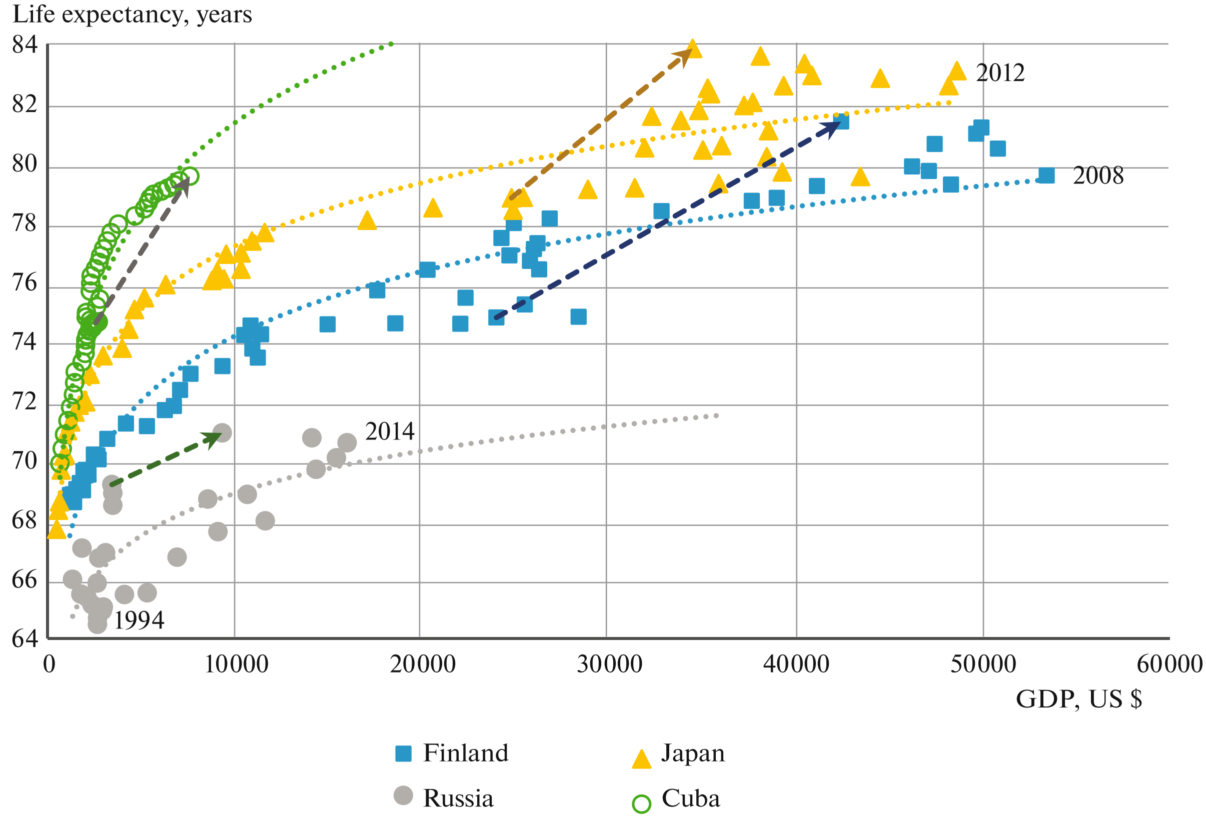

Fig. 5. Trends in the relationship between life expectancy and GDP in particular countries according to data related to different years (1960–2015) (for Russia, the data series begins in 1989). The dashed arrows compare the situations as of 1989 and 2015 in each country. They all indicate a trend toward increases in both GDP and life expectancy over time, but their positions are random, because they depend on the initial and final compared points. For example, if we compare 1994 and 2014 for Russia instead of 1989 and 2015, the arrow's position will be different. However, what matters here is the relationship of the parameters with each other, not with time, with account for that over time they grow nonmonotonously and can significantly fluctuate, as shown in Fig. 6.

than two times in 10 years, whereas the Preston curve suggests that membership in the 80+ Club requires about two times more than a doubling.

So, what can we do to join this 80+ Club? An increase in the GDP to a level of at least 20000 US $ per year is absolutely necessary, but certainly not sufficient. To make an idea on what else could be done, one can look at the countries that are about to join the Club and have the same or lower GDP. Earlier, the Mediterranean and Caribbean were mentioned, but there is no need to look so far since we have the Northern Caucasus. The conditions there are favorable. It is known that living in high mountains promotes longevity [3, 23, 28], as do religiousness and respect for traditional values [1, 21, 27]. However, these factors are counter-indicative in terms of increasing GDP. Anyway, it is impossible to create the same conditions as in the Northern Caucasus (or Greece and Costa Rica) for all of Russia.

It is worth mentioning that the republics of the Northern Caucasus belong to the most highly subsidized regions of the Russian Federation. Could it be that people there live longer due to subsidies rather than GDP? However, the republics of Sakha and Tuva are also highly subsidized, but this does not promote longevity there. We may look at data about the relationship between life expectancy and monetary income per capita, assuming that subsidies are transformed into wages. However, there is no sense in showing the result, because it is practically the same as that inferred from points that represent the Russian regions in Fig. 2. Salary in the North Caucasus is very low, so as GDP is, whereas Nenets citizens do not benefit from their salary at all in terms of longevity. Again, it is impossible to subsidize all regions.

Maybe it is not GDP as a whole but rather annual per capita healthcare spending? Such statistics is also available. The statistics suggests that healthcare spendings are proportional to GDP in all countries, including Russia, so consistently (Fig. 7) that the Preston curve based on these assumptions does not look interesting. In this case, Russia is as close to the bottom as in the classical one. The same follows from examination of data on healthcare spendings in partic-

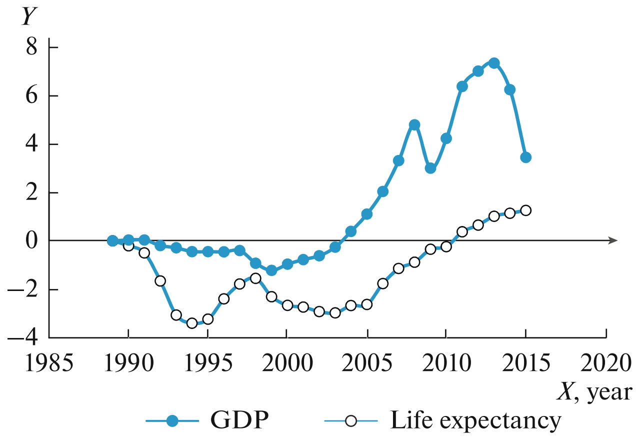

Fig. 6. Relative deviations of GDP and life expectancy by years from their levels as of 1989. $Y = A_X/A_{1989} - 1$, where A is the value of life expectancy or GDP according to the World Bank data, and X is the year to which the data relate. Life expectancy deviations are multiplied by 5 to make them comparable with those related to GDP.

ular countries in comparison with the life expectancy in different years, instead of healthcare spendings in different countries in a particular year. However, the results of the former analysis are so illustrative, that it makes sense to show some of them (Fig. 8).

The data in Fig. 8 show that the life expectancy trend in Tajikistan, where GDP and healthcare spending are much lower now than in Russia, the ratio between the two parameters being the same ratio as in Russia and Finland (Fig. 7), upon reaching the same GDP as in Finland and Japan will nearly coincide with the trends in these countries. Moreover, the same is true even for the Republic of Congo, where healthcare spending is meager and life expectancy is correspondingly short. However, this is not true for Russia, where the trend of life expectancy over 20 years from 1995 through 2014 did not change; therefore, healthcare spending at the level of 80+ Club members will not result in the desired 80 years of life expectancy.

It thus has to be admitted that the investment of available resources in human life expectancy (i.e., life

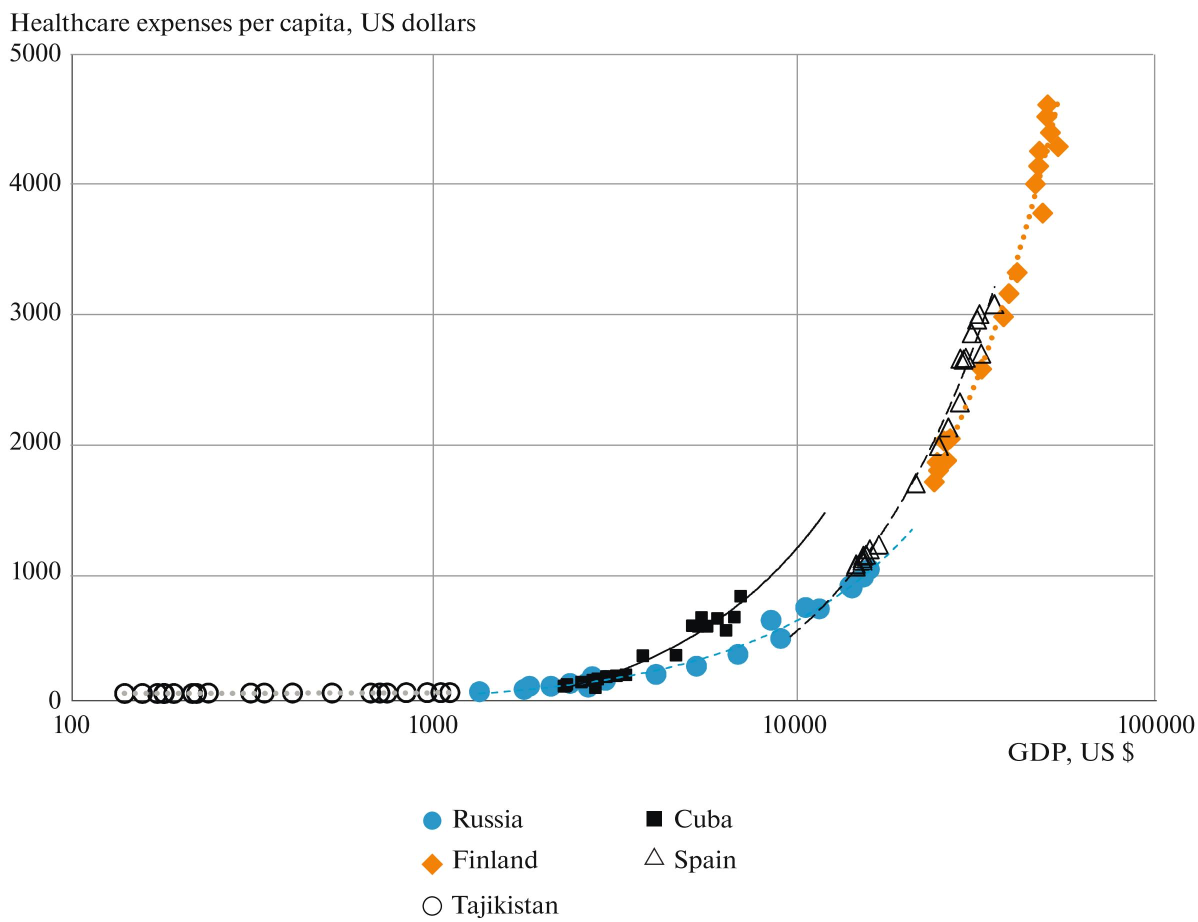

Fig. 7. Dependence of healthcare spending on GDP. The GDP scale is logarithmic to better illustrate the trend of Tajikistan, which in the linear scale is compressed to a point. It can be seen that Tajikistan, Russia, and Finland with their absolutely different GDP ranges and natural conditions have a common trend of relationship between healthcare spending and GDP. The Cuban trend somewhat deviates from the segment of the general trend, which includes Russia, due to an increased proportion of healthcare spending relative to GDP.

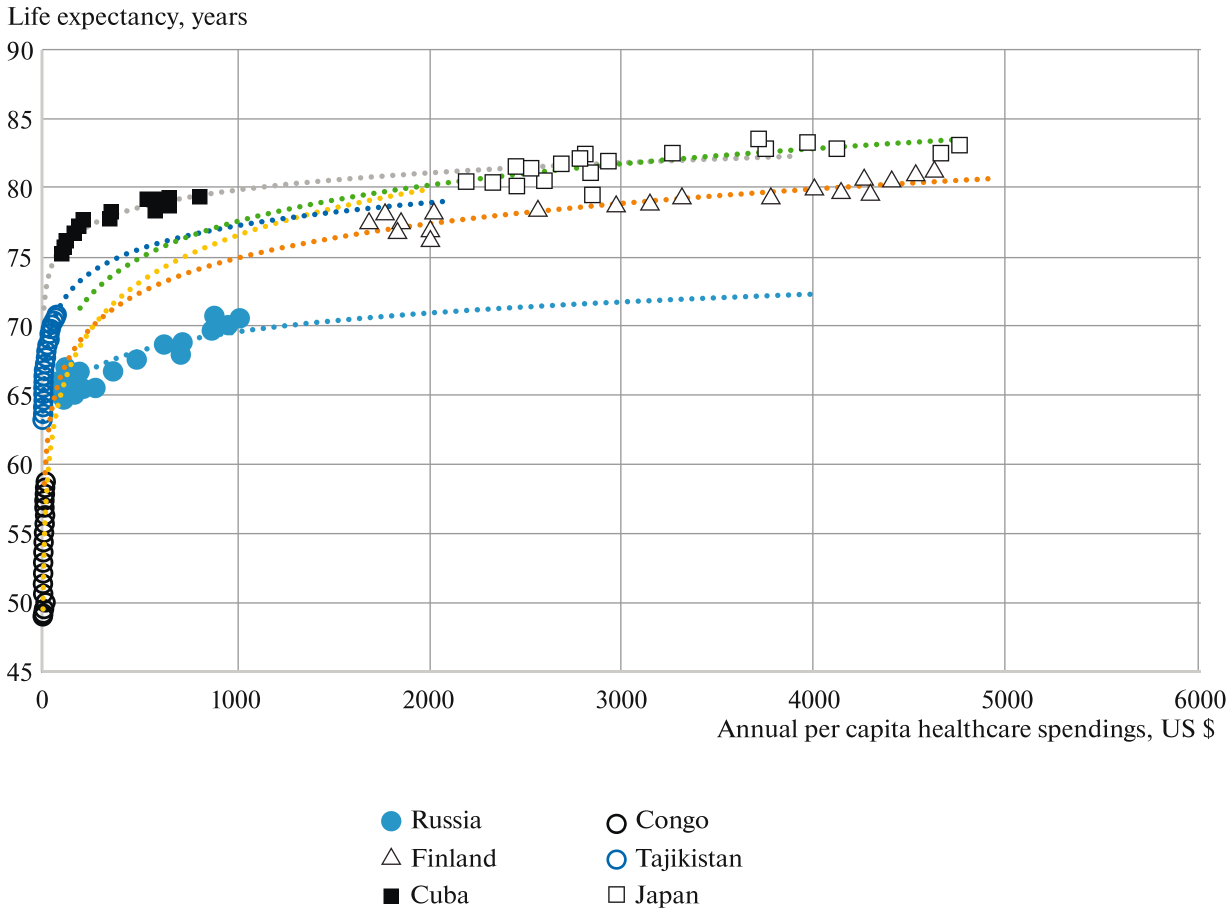

Fig. 8. Relationship between healthcare spending and life expectancy in particular years in particular countries. The dashed lines represents the corresponding logarithmic trends.

quality) is less effective in Russia than in other countries, from Congo to Finland. That is why it is impossible to bring Russia to the 80+ Club merely by increasing GDP and healthcare spending. Healthcare spending in the United States (9400 US $ in 2014) is two times higher than even in Finland, whereas life expectancy (78.74 years) falls short of 80. Well, let the United States deal with their problems. What shall we do about ours?

First, we have to acknowledge that they exist.

One can imagine at least two extreme variants of our problems. If we assume that healthcare spendings are used as allocated, then it turns out that the major part is spent for nothing where the quality of life and lifestyle make healthcare helpless. If we assume that life quality and conditions generally correspond to GDP and are favorable for the assimilation of investments in healthcare, then it turns out that healthcare spendings go astray. Measures to remedy the situation depend on the variant that is prevalent. If particular situations are not distinguished but instead painted with the same brush (which is quite probable, because this is easier for the authorities), the expenditure of funds would be useless for society, though possibly not so much for certain natural and juridical persons.

There is no doubt that the priority of membership in the 80+ Club established at the political level will activate those who propose to increase life expectancy by "decelerating the aging process" and would like to divert resources to devising means for "slowing down the program of aging," "increasing the nonspecific resistance of the body," etc. The ignorance of natural science at the levels at which decisions are made regarding the allocation of both public and private funds for the support of research and development makes such proposals very attractive. Lawyers, economy experts, and managers are too busy with law enactment and abiding to pay attention to the laws that exist independently of, and beyond the reach of, their consciousness.

The amount of arguments to be taken into consideration in making informed decisions regarding increases in life expectancy is too large to be encompassed in one article. An analysis of the current scientific literature, which is indispensable in the present case, will be limited below to a few principal claims, which are still debatable.

The parameters of the distribution of the number of people over lifespan is defined by the Gompertz–Makeham law (in the first approximation, the probability of death at ages from 25 to 85 years increases exponentially with a doubling period of 7–8 years), which is affected, but not cancelled, by additional circumstances. These parameters are such that the maximum lifespan of humans as representatives of a certain biological species is 110–120 years, higher ages at death being extremely rare. The average or median lifespan, upon no contribution of the age-independent mortality, is around 85 years and is practically unchanged when the lifespans of rare record holders in longevity increase [5, 7, 8, 15, 19, 26].

A program of aging, which leads to death at a certain age or in certain circumstances and presumably can be slowed down or even eliminated, could have arisen in the evolution of some species under particular ecological conditions, but not those that took place in the process of transformation of apes into humans [13, 17].

Aging is not a result of an evolved program that limits the span of life or optimizes the distribution of resources available to an organism for self-preservation, self-maintenance, and investment in offspring in such a way as to maximize self-reproduction. Aging is the result of fundamental limitations imposed on evolutionary possibilities by the physical and chemical properties of the molecules involved in the performance of biological functions [8, 10, 11, 13].

So far, the increase in human life expectancy was not accompanied by a deceleration of aging, but rather it was associated with a decrease in the age-independent mortality [13, 14, 16]. The life expectancy of a population as a whole generally increases each time a possible death is prevented by appropriate measures, including medical interventions. This is exactly what largely drove the increase in life expectancy; the lower the life expectancy is, the larger is this reserve, all else being equal.

Successful attempts to increase the lifespans of experimental animals via genetic manipulations are hardly relevant to real measures applicable to humans, and the magnitude of effects achieved by pharmaceutical measures decreases in series from simple organisms to more complex ones [12, 15].

Many initially impressive results in lifespan prolongation were not reproduced subsequently, there being specific reasons for that [20].

Real measures for increasing human life and health spans have been known for a long time. Science merely separates facts from speculations, provides accurate statements, explains effects where there are any, and defines the limits of what is possible. On reaching a GDP of around 10000 to 20000 US $, the increase in life expectancy is limited not by the economy or biomedical research and developments, but by social and personal recognition of already known results [12, 14].

The reallocation of limited resources to education (and, correspondingly, the conscious improvement of lifestyle) and to the prevention and treatment of the most common diseases is more effective in increasing life expectancy than distracting the resources towards advertising of expensive medical achievements in life prolongation in extremely severe cases and towards developing and testing of universal antiaging remedies [15].

In conclusion, the following citation from the article that laid the basis of modern insights in the evolutionary background and nature of aging [25] would be relevant: “Such conclusions are always disappointing, but they have the desirable consequence of channeling research in directions that are likely to be fruitful.”

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare that they have no conflict of interest. *Statement of the welfare of animals*. This article does not contain any studies involving animals or human participants performed by any of the authors.

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