THE INFLUENCE OF CLIMATE ON THE DETERMINATION OF THE
UPPER PERMISSIBLE FLUORIDE LEVEL IN POTABLE WATER IN SUDAN

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SUMMARY: The incidence of dental fluorosis in Sudan ranges from 4.5–100% depending on the fluoride level in potable water. The present study was designed to determine the maximum safe level for fluoride in potable water under the conditions currently prevailing in the affected areas using the Galagan and Vermillion equation which permits the calculation of the upper permissible fluoride level as a function of temperature. The annual mean maximum temperature (AMMT) in Sudan during the last 10 years, from data in the database bank of the American Central Intelligence Agency, was 35.58°C which gave an upper permissible fluoride level in potable water of 0.61 ppm. However, after applying a correction factor of 0.56 to the equation to allow for the current Sudanese conditions, an upper permissible limit for fluoride in potable water was found of 0.32–0.35 mg/L. The people in fluoride endemic areas in Sudan should not drink water with a fluoride level above 0.35 mg/L to avoid the risk of fluorosis.

Key words: Fluorosis; Sudan; Upper permissible fluoride concentrations.

INTRODUCTION

Fluoride is widely distributed throughout the world and never occurs in a free state in nature. Although it accumulates in hard tissues, it is not considered to be an essential trace element or required for the development of healthy teeth or bone. The excessive consumption of fluoride can put the mineralized tissues at risk of developing fluorosis. Dental fluorosis is viewed as principally affecting the permanent dentition, while very high fluoride levels (>10 ppm) are required in potable water for the fluoride to cross the placental barrier and affect the primary dentition. Multiple mechanisms, including direct fluoride-related effects on ameloblasts during the secretory and maturation phases, indirect fluoride-related effects on the forming matrix (nucleation and crystal growth in all stages of enamel formation), and calcium homeostasis, can result in dental fluorosis depending on the dose and duration of fluoride exposure.

In clinical terms, dental fluorosis may result in varying degrees of structural damage, superficial porosity, and loss of continuity of the dental enamel layer. Dental fluorosis may be more than a cosmetic effect and cause psychological trauma, particularly amongst adolescents. If a sufficient amount of fluorotic enamel is fractured and lost, dental fluorosis may cause pain, adversely affect food choices, compromise chewing efficiency, and require complex dental treatment. Many local inhabitants in areas with high potable water fluoride levels demand that their teeth be extracted and replaced with dentures.

Dental fluorosis is therefore a global public health issue that is predominantly observed in areas with high potable water fluoride levels water. Observational

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The influence of climate on the determination of the upper permissible fluoride level in potable water in Sudan

Ramadan, Hilmi

studies in the United States in the first half of the 20th century revealed an inverse correlation between the fluoride content in the water supply and the mean number of decayed teeth among the population. However, it was found that above a certain concentration, the occurrence of caries ceased to significantly diminish, while the prevalence of dental fluorosis significantly increased. Although the topical action of fluoride is now considered to have a greater dental effect than that following systemic absorption, these studies were used to estimate the fluoride level that would provide the maximum benefit of reduction in caries with the minimum risk of dental fluorosis.

Galagan and Vermillion proposed a formula to establish the upper permissible fluoride level, which correlated the fluid intake and the mean air temperature. However, it should be emphasized that their calculations were based on the temperature variations in the USA, which has a temperate climate. Thus, depending on the climatic conditions and fluoride ingestion from other sources, an upper permissible fluoride level of 0.5–1 ppm in potable water has been recommended. A Pakistani study on the appropriate fluoride concentration in potable water, applying a modified Galagan’s equation, determined the upper permissible fluoride concentration to be 0.35 ppm. Therefore, it is of the utmost importance to determine the fluoride levels in natural potable water supplies in a community, to prevent excessive fluoride intake.

A series of studies on fluoride and fluorosis in Africa demonstrated varying degrees of prevalence of dental fluorosis. Manji et al. observed 100% dental fluorosis in Kenyan children (6–15 years of age) living in a village 2095 m above sea level and consuming water with a fluoride level 2.0 ppm. Moller et al. reported dental fluorosis in 90% children in a Ugandan village where the fluoride content of potable water was 2.0–3.0 ppm. Furthermore, Moller et al. examined children in low-fluoride areas in Uganda, and reported great variations, in which the prevalence of dental fluorosis varied between 3.4–42.5% in villages consuming water with fluoride levels between 0.17–0.30 ppm. Manji et al. demonstrated dental fluorosis in 78% of the children from a Kenyan village with a fluoride level between 0.10–0.46 ppm in the potable water. Similar findings have also been reported from Tanzania and Sudan.

As indicated above, the relationship between the fluoride concentration of water and dental fluorosis is complex. With a given fluoride concentration, the prevalence and severity of fluorosis seems to increase with increasing mean daily temperature, and altitude above sea level. Nutritional status may also play a role in the development of dental fluorosis. Undoubtedly, however, potable water is the most important single provider of fluoride to children in areas with endemic dental fluorosis. Knowledge of the upper permissible fluoride content of the potable water is therefore needed in all studies on dental fluorosis.

A prevalence of 61% dental fluorosis was first reported in the Sudan 1953, by Smith et al. who examined schoolboys in the Butana. The relevant water sources contained fluoride in the range of 1.1–4.0 ppm. According to the generally held opinion, Smith et al. considered a water fluoride level of less than 0.8 ppm to be
harmless, and therefore could not explain why 61% of the boys living in a village with only 0.65 ppm in the potable water developed dental fluorosis. In 1966 Emslie found fluoride levels in Sudanese potable water of up to 5 ppm and reported a prevalence of 90% dental fluorosis in the Butana.16 Aziz Ghandour and coworkers found a fluorosis prevalence of 64% in boys and 50% in girls from Omdurman,14 while El-Hassan found dental fluorosis only in 4.5% of the children in neighbouring Khartoum.15

Ibrahim et al. studied the fluoride levels of potable water in two Sudanese villages, Treit el Biga (TeB) and Abu Groon (AG), and assessed the prevalence and degree of dental fluorosis in children who were born and raised in the villages.19 The water in TeB was shown to have a low, very stable fluoride concentration of 0.25 ppm, whereas AG had a tenfold higher, and slightly varying, fluoride level of 2.56 ppm. The study recorded dental fluorosis on the maxillary central incisors according to Dean’s index. In TeB, 91% of the children showed signs of dental fluorosis whereas in AG all children had fluorotic teeth. On the other hand, another study in TeB revealed a fluoride level of 0.45 ppm and a prevalence of dental fluorosis of 30%.20

So far, dental fluorosis is a public health problem in only a few Sudanese localities and results from a high consumption of fluoride from naturally fluoridated water or the uncontrolled consumption of fluoridated products, particularly toothpaste.21, 22

Awareness of the upper permissible level for fluoride is of the greatest importance, principally in fluorotic zones of tropical countries such as Sudan. Using clinical dental fluorosis as the most convenient biomarker of fluoride exposure, the objectives of the present study were:

To determine the upper permissible level of fluoride in potable water in the Sudan using the modified equation of Galagan and Vermillion7

To provide baseline data and information about dental fluorosis to public health authorities.

MATERIALS AND METHODS

Four bibliographic databases of scientific literature for clinical, experimental, and review reports, using the search term “fluorosis and Sudan” were used. The four databases were:

(1) MEDLINE (compiled by the National Library of Medicine of the United States); (2) PubMed (also compiled by the National Library of Medicine of the United States); (3) Google scholar and (4) HINARI (Health Internetwork, WHO). With the articles located through these means of searching, we reviewed all the references that they cited. Data on fluoride concentrations in potable water for the cited locations was derived from seven areas (Khartoum, Port Sudan, Nyala, El-Fasher, Kassala, Atbara and El-Obeid) mentioned in earlier studies and which demonstrated that these areas had varying concentrations of fluoride in the potable water.
In order to calculate the upper permissible level of fluoride in potable water for Sudan we used the modified equation of Galagan and Vermillion\textsuperscript{7} which allows the calculation of water intake as a function of temperature. Annual mean maximum temperatures (AMMT) recorded during the last 10 years from seven cities; Khartoum, Port Sudan, Nyala, Kassala, Atbara, El-Fasher and El-Obeid; were obtained from the CIA databank (https://www.cia.gov/library/publications/the-world-factbook/geos/su).

If the original metric units employed by Galagan and Vermillion\textsuperscript{7} are converted to SI units, the equation to calculate the optimal upper level of fluoride in potable water (mg/l) becomes:

\[
\text{Optimal upper level for fluoride concentration} = \frac{0.022}{(0.0104 + 0.000724 \times \text{AMMT}^\circ \text{C})}
\]

The original formula by Galagan and Vermillion\textsuperscript{7} estimated the daily water intake under different temperature conditions in United States during the late 1950s. This equation was proposed for American children, who were presumed to take 44\% of their total fluid intake as milk with negligible fluoride levels. For the vast majority of the Sudanese population, milk is a luxury and even when infants are given milk it is diluted with water. Therefore, in Sudan, the true water intake by children is probably similar to the study carried out in Chile by Villa et al.\textsuperscript{23}

Therefore, a factor of \(1 - 0.44 = 0.56\) was applied to the original equation. This modification allows for the fact that under current Sudanese conditions almost all the children’s fluid intake comes from potable water. The modified equation used to calculate the optimal upper level of fluoride in potable water of Sudan was:

\[
\text{Optimal upper level for fluoride concentration} = \frac{0.022 \times 0.56}{(0.0104 + 0.000724 \times \text{AMMT}^\circ \text{C})}
\]

RESULTS

The annual mean temperature recorded during the last 10 years were collected from seven cities: Khartoum, Port Sudan, Nyala, Kassala, Atbara, El-Fasher and El-Obeid (Table 1). The annual mean maximum temperature for each city was also recorded (Figure 1). The AMMT of Sudan was found to be 35.58\(^\circ\)C. According to the original formula of Galagan and Vermillion,\textsuperscript{7} the recommended upper permissible level of fluoride in potable water in Sudan was calculated to be 0.62 ppm. However, using the modified version of the equation\textsuperscript{9} by applying the multiplication correction factor of 0.56, the upper permissible fluoride level in potable water in Sudan, under the current Sudanese conditions, was found to be 0.35 ppm (Table 2).
The influence of climate on the determination of the upper permissible fluoride level in potable water in Sudan
Ramadan, Hilmi

Table 1. Mean temperature in degrees Celsius during a ten year period

<table>
<thead>
<tr>
<th>City</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Mean</th>
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<td>36</td>
<td>40</td>
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<td>42</td>
<td>38</td>
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<td>36.8</td>
</tr>
<tr>
<td>Port Sudan</td>
<td>27</td>
<td>27</td>
<td>30</td>
<td>33</td>
<td>38</td>
<td>40</td>
<td>43</td>
<td>42</td>
<td>39</td>
<td>34</td>
<td>31</td>
<td>28</td>
<td>34.3</td>
</tr>
<tr>
<td>Nyala</td>
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<td>32</td>
<td>36</td>
<td>39</td>
<td>38</td>
<td>37</td>
<td>33</td>
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<td>33</td>
<td>35</td>
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<td>37</td>
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<td>37</td>
<td>37</td>
<td>35</td>
<td>36.9</td>
</tr>
<tr>
<td>Atbara</td>
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<td>41</td>
<td>43</td>
<td>43</td>
<td>41</td>
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<td>42</td>
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<td>36</td>
<td>32</td>
<td>38.2</td>
</tr>
<tr>
<td>El-Fasher</td>
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<td>32</td>
<td>35</td>
<td>38</td>
<td>38</td>
<td>35</td>
<td>32</td>
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<td>36</td>
<td>33</td>
<td>31</td>
<td>34.5</td>
<td></td>
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<tr>
<td>El-Obeid</td>
<td>31</td>
<td>32</td>
<td>36</td>
<td>38</td>
<td>39</td>
<td>37</td>
<td>33</td>
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<td>34</td>
<td>36</td>
<td>34</td>
<td>31</td>
<td>34.3</td>
</tr>
</tbody>
</table>

Figure 1. Annual mean maximum temperature during a ten year period.
DISCUSSION

In Sudan no artificial fluoridation projects are in place as the natural fluoride level in the potable water is above the upper permissible level and dental fluorosis is present in many parts of the country, particularly in various parts of Kordofan, Darfur, El-Butana, and Khartoum state (Abu Garoun, Um Dawanban and Abu Deliaq).\textsuperscript{14, 16, 21, 22}

Underground water has been underground for many thousands of years and is therefore effectively influenced by its immediate components. Geologically, the East African bedrock is fluoride rich due to its volcanic origin. The range of fluoride levels in east Africa varies is 0.1–10 mg/L. The wells examined in Sudan are mainly found within areas dominated by Nubian sandstone. Fluoride containing aquifers may be found in such sandstone, but high-fluoride levels in potable water are much less prevalent in the Sudan compared to the levels in countries that are within the East Africa Rift Valley.

The highest fluoride level found in Sudanese studies was 4 mg/L.\textsuperscript{18} Other studies in Sudan have reported varying levels of fluoride in potable water in the Western states of Sudan (Kordofan and Darfur) where areas of pockets of volcanic basalt may be found.\textsuperscript{22}

The WHO reported an upper permissible level of 1.5 mg/L of fluoride in potable water in temperate climate conditions. However, under tropical conditions where water consumption increases the fluoride levels need to be reduced.\textsuperscript{23} Since water is a public asset that is indispensable for life, its importance for public health is widely recognized but more than one billion people worldwide do not have access to safe water. The fluoride concentration is an important parameter for the quality assessment of potable water because of its potential to cause dental fluorosis, and other adverse health effects, when present at high levels. The establishment of safe levels for fluoride in potable water is an essential measure for protecting human health.\textsuperscript{24}

The Nile rivers are the main source of water in the Sudan but most Sudanese communities outside the Nile valley depend on ground water. As compared with the local surface water, ground water is, on an average, richer in fluoride. The

<table>
<thead>
<tr>
<th>City</th>
<th>Mean temperature (°C)</th>
<th>Optimal [F] (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Khartoum</td>
<td>36.8</td>
<td>0.33</td>
</tr>
<tr>
<td>Port Sudan</td>
<td>34.3</td>
<td>0.35</td>
</tr>
<tr>
<td>Nyala</td>
<td>34.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Kassala</td>
<td>36.9</td>
<td>0.33</td>
</tr>
<tr>
<td>Atbara</td>
<td>38.2</td>
<td>0.32</td>
</tr>
<tr>
<td>El-Fasher</td>
<td>34.5</td>
<td>0.35</td>
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<tr>
<td>El-Obeid</td>
<td>34.3</td>
<td>0.35</td>
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</tbody>
</table>
fluoride content of Nile waters fluctuates between 0.2 and 0.4 mg/L. However, it has been indicated in previous studies that fluoride values as high as 1.0 mg F/L may be recorded, especially when the water level in the Nile rivers is low.

Dental fluorosis has been reported in Sudan since the 1950’s among children in certain areas, especially in Northern, Western Sudan, and areas around Khartoum.

The presence of high fluoride levels in the potable water sources in the fluorotic zones of tropical countries is a problem in providing safe water to the community, particularly in rural areas, where groundwater sources remain the only source of potable water. It has been shown that there is a statistically significant increase in the prevalence of dental fluorosis with increased fluoride levels in drinking water, increased age, and longer duration of residence in a particular area.

The exposure to fluoride in the modern world has expanded far beyond the degree investigated by the fluoride pioneers 60 years ago. They dealt most exclusively with fluoride in drinking water, and their careful research on the appropriate concentrations was conducted from that viewpoint.

The debate on the optimal level of fluoride in potable water began with Dean’s 21-city study in the United States. Based on a comprehensive review of his work, Dean recommended that the fluoride in potable water of the United States might be adjusted to 1.0 ppm in order to achieve maximum benefit of caries protection and a minimum risk of acquiring fluorosis. The basis of his recommendation was that 1.0 ppm level of fluoride in the potable water gave near maximal reduction of caries, i.e., 60% and only ‘sporadic instances of the mildest form of dental fluorosis of no practical or aesthetic significance were observed’. He further showed that there is very little advantage to be gained in further reducing caries by using water higher in fluoride concentration than about 1 ppm, as the risk of acquiring fluorosis increased considerably. Based on this dose–response relationship, the optimal level of fluoride in potable water was first recommended.

However, a critical review of the classical studies of Dean, revealed that Dean’s data had only three observation points between 0.5 and 0.9 ppm, and none between 0.9 and 1.2 ppm. A subsequent study, which had 15 data points over the critical range, suggested that caries declined only marginally between 0.6 and 1.2, and concluded that an appropriate trade-off between dental caries and fluorosis occurs at around 0.7 ppm.

Galagan and Vermillion noted that varying concentrations of fluorosis existed at the same level of fluoride concentration in different temperature zones. They collected data on the drinking habits of children in different temperature conditions. The aggregate data were used to formulate a range (0.7–1.2 ppm) of optimal fluoride concentrations for mean maximum temperatures between 50 and 90ºF. The optimal level of fluoride in potable water has since then universally been calculated by applying the equation of Galagan and Vermillion, which permits the
calculation of water intake as a function of temperature. Studies have shown that these guidelines cannot be universally applied, especially in hot tropical countries.

A fluoride level of 0.7–1 ppm, which is considered optimal for Austria, may be considered to be too high for Bophuthatswana and Sudan, where fluorosis has been observed at 0.5 ppm. Upper limits of fluoride in the potable water of Senegal have been recommended at 0.6 ppm. In Sri Lanka, the recommended level of fluoride in potable water is 0.6–0.8 ppm, while in Chile the optimal level is recommended at 0.5–0.6 ppm. Fluorosis was seen in 100% of children drinking potable water with 2 ppm of fluoride in Kenya, while an optimal level of 0.34 ppm was calculated for a fluorotic zone of western India.

The World Health Organization has more recently recommended a much more conservative range of 0.5–1.0 ppm.

Smith et al. in 1953 were the first to report on the prevalence of dental fluorosis in the Sudan during their study of schoolboys in the Butana region where the prevalence of fluorosis was stated to be 60.6%. The relevant water sources in the area contained fluoride levels in the range of 1.1 to 4.0 mg/L. Smith et al. considered that fluoride concentrations of less than 0.8 mg/L were safe, and as a result had problems in explaining the fact that five (out of eight) boys living in a village with only 0.65 mg/L in the potable water developed dental fluorosis.

Fluoride levels in potable water of up to 5 mg/L have been reported by Emslie who demonstrated a prevalence of 90% fluorosis in one area. Aziz Ghandour et al. studied children in Umdurman and found a dental fluorosis-prevalence of 64% in boys and 50% in girls. El-Hassan, on the other hand, found a dental fluorosis prevalence of only 4.5% in the children in neighbouring Khartoum. The fluoride levels of the relevant potable water was not mentioned but both cities were expected to have obtained their water from the same source, the river Nile.

The upper permissible level of fluoride in potable water is commonly calculated by applying the equation of Galagan and Vermillion, which allows the calculation of water intake as a function of temperature. In this study, the annual mean maximum temperatures (AMMT) recorded during the last 10 years were obtained from the CIA databank (https://www.cia.gov/library/publications/the-world-factbook/geos/su). The average AMMT of Sudan was 35.6ºC (http://www.climatetemp.info/sudan/) at which the upper permissible fluoride level in potable water of Sudan is found to be between 0.5–0.7 mg/L.

The standards of the calculations were based on the original formula by Galagan and Vermillion, which estimated the daily water intake under different temperature conditions in the United States during the late 1950s. This equation was proposed for American children, who were presumed to take 44% of their total fluid intake as milk with negligible fluoride levels. However, for the vast majority of the Sudanese population, milk is a luxury, and even when infants are fed milk it is diluted with water. In Sudan, the true milk intake by children is probably similar to that the study carried out in Chile by Villa et al. who used a
modified Galagan’s equation and found the upper permissible potable water fluoride level to be in the range 0.5–0.6 mg/L.\textsuperscript{33}

As, under current Sudanese conditions, almost all the fluid intake for Sudanese children comes from potable water, the Galagan and Vermillion\textsuperscript{7} equation was modified with a correction factor of 0.56 resulting in an upper permissible potable water fluoride level range of 0.32–0.35 ppm.

There is, therefore, no gold standard for setting up a universal upper permissible potable water fluoride level. Determining the most appropriate fluoride concentrations in potable water is critical for communities. However, the extreme heterogeneity in findings, across various countries, makes the delineation of exact criteria and universal guidelines particularly difficult, and suggests the need for a more practical approach. It is consequently necessary that each country calculates its own upper permissible level of fluoride in potable water by considering the prevalence of dental fluorosis. Climatic conditions, dietary habits of the population, and other possible fluoride exposures also need to be considered in formulating these recommendations.

**CONCLUSIONS**

1. There is, therefore, no gold standard for setting up a universal upper permissible level of fluoride in potable water.

2. Determining the upper permissible level fluoride levels in potable water is critical for communities but the extreme heterogeneity in findings, across various regions of the Sudan, makes the definition of unequivocal criteria and general guidelines particularly difficult.

3. It is very important that each region calculates its own upper permissible level fluoride level in its potable water.

4. Using the guideline by Dean and corrected for the temperature in Sudan, our results indicate that the recommended upper permissible level of fluoride in potable water of Sudan may be set between 0.32 and 0.35 ppm.

5. Climatic conditions, dietary habits of the population, and other possible fluoride exposures also need to be taken into account in formulating the recommendations.

6. The results show that no common guidelines on the upper permissible water fluoride levels can be followed without a previous thorough analysis of all other fluoride sources available to each community.

**RECOMMENDATIONS**

1. There is an obligation to provide information to the public by all levels of government (federal, state, and local), and other interested parties to ensure that the naturally occurring fluoride levels are not above the upper permissible level. This process, by means of definite legislation, will establish vital support leading towards examining and defining the quality standards for mineral water usage in Sudan.
2. Further research is clearly needed before authoritative recommendations can be made regarding the use of fluorides, including the recommended upper permissible dietary intake of fluoride.

3. Further longitudinal studies are needed to determine the safe fluoride levels for the general public in Sudan, taking in account age, nutritional status, altitude, geographical location, and weather, among other factors.

REFERENCES:

The influence of climate on the determination of the upper permissible fluoride level in potable water in Sudan
Ramadan, Hilmi