DNA as a Supramolecule for Long-Distance Charge Transport

Bernd Giese*, Eric Meggers, Stefan Wessely, Martin Spormann, and Andreas Biland

Abstract: Electron transport through DNA occurs over very long distances (100 Å and more). The process follows a hopping mechanism and depends upon the DNA sequence. The efficiency of the charge transport is only slightly distance dependent because in most cases the H_2O trapping of the charge is slower than the electron transfer. These findings show the potential of substituted DNAs as new materials for nanoelectronics in the future.

Keywords: DNA · Electron transfer · Hopping mechanism · Supramolecular chemistry

1. Introduction

The question of whether DNA is a supramolecule allowing long-distance electron transfer was the subject of controversial debate in the 1990's [1]. We entered this area three years ago by studying radical-induced DNA strand cleavage reactions. Our experiments showed that a positive charge can be injected into DNA starting from 4'-DNA radicals [2]. This led to an assay which made it possible to follow the charge migration through DNA over long distances. In order to understand the experimental results we suggested in 1998 a hopping mechanism [3] for long-distance charge transport through DNA that was based on theoretical studies of Jortner *et al.* [4]. A similar hopping mechanism, which is slightly different in the details, was also suggest-

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ed by Schuster [5] and today there is a consensus that long-distance electron transport through DNA occurs by a hopping mechanism and that the base sequence plays an important role.

2. The Assay

The assay that we have developed to study the charge transfer through DNA is quite different from previous methods (Scheme 1). We generate the charge by site-selective formation of 4'-DNA radical **2** starting from the acyl-substituted DNA **1**. In an intramolecular, heterolytic C,O-bond cleavage reaction, radical **2** generates the sugar radical cation **3** that either reacts with H_2O or is reduced in a single electron transfer (ET) step. The trapping reaction with H_2O occurs with a rate of about 10^8 s^{-1}, leading to products **5** and **6** [2]. If the ET reaction is in this order or faster, the sugar enol ether **4** is formed (Scheme 2).

Experiments with DNA strands **7** have demonstrated that ET reactions from adjacent DNA bases (X), which are about 7 Å away from the sugar radical cation, can compete with these H_2O trapping reactions only if their ionization potentials are equal or smaller than that of guanine (G). With guanine as the adja-
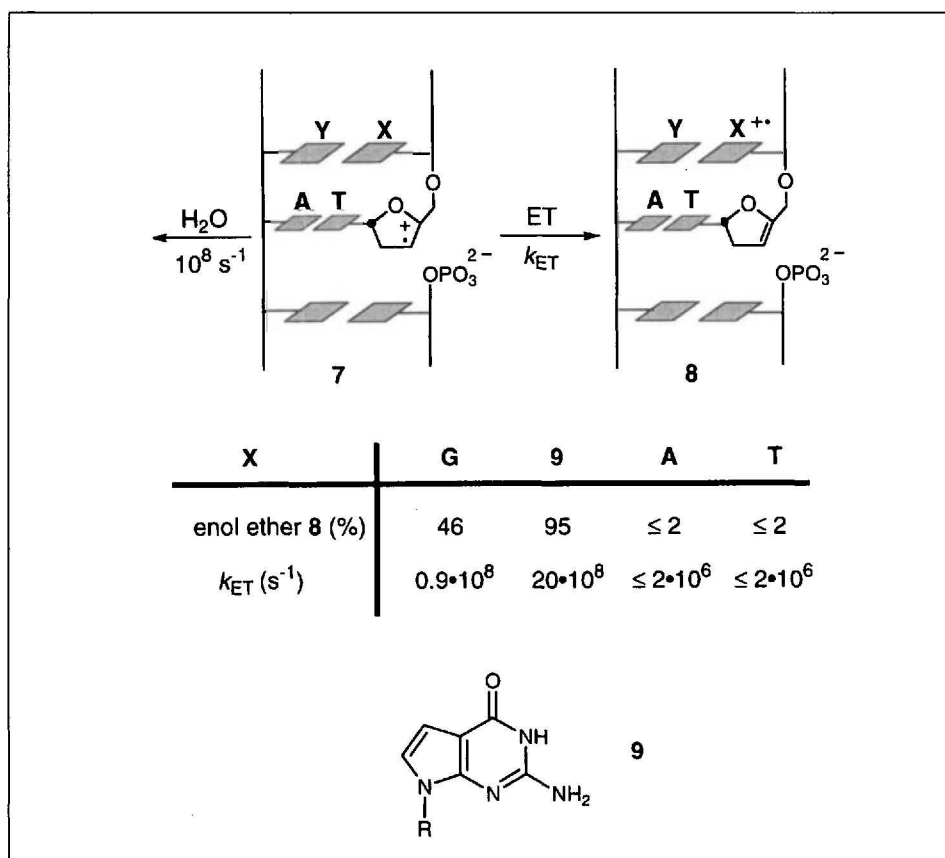
cent base, the radical cation **7** yielded 46% of enol ether **8**, and 7-deazaguanine **9**, which has a considerably lower ionization potential [6], led to enol ether **8** in nearly quantitative yield (Scheme 3). Because the H_2O trapping rate of the sugar radical cation **7** does not depend much upon the variation of the adjacent base, the electron transfer rate increases by a factor of 22 if the guanine is exchanged by 7-deazaguanine **9**. However, with adenine or thymine as a base, no enol ether **8** was observed (Scheme 3). Obviously, the ionization potentials of adenine and the pyrimidine bases are too high for a competition of electron transfer with the H_2O trapping reaction of **7** [7]. Thus, the H_2O reaction acts as a filter and leads to a selective oxidation of G in DNA strands **7** that contain only the four natural bases.

In order to measure ET reactions that are induced by a guanine radical cation $G^{•+}$ and not by the sugar radical cation **7**, we translocated the positive charge to a guanine of the complementary, radiolabeled strand (**10**→**11**). The $G^{•+}$ in **11** also reacts with H_2O, although with a lower rate than the sugar radical cation **3**. This leads to an oxidized guanine that can be detected by base-induced strand cleavage. In competition with this H_2O trapping, an ET reaction occurs from a GGG sequence (**11**→**12**) [3] (Scheme 4).
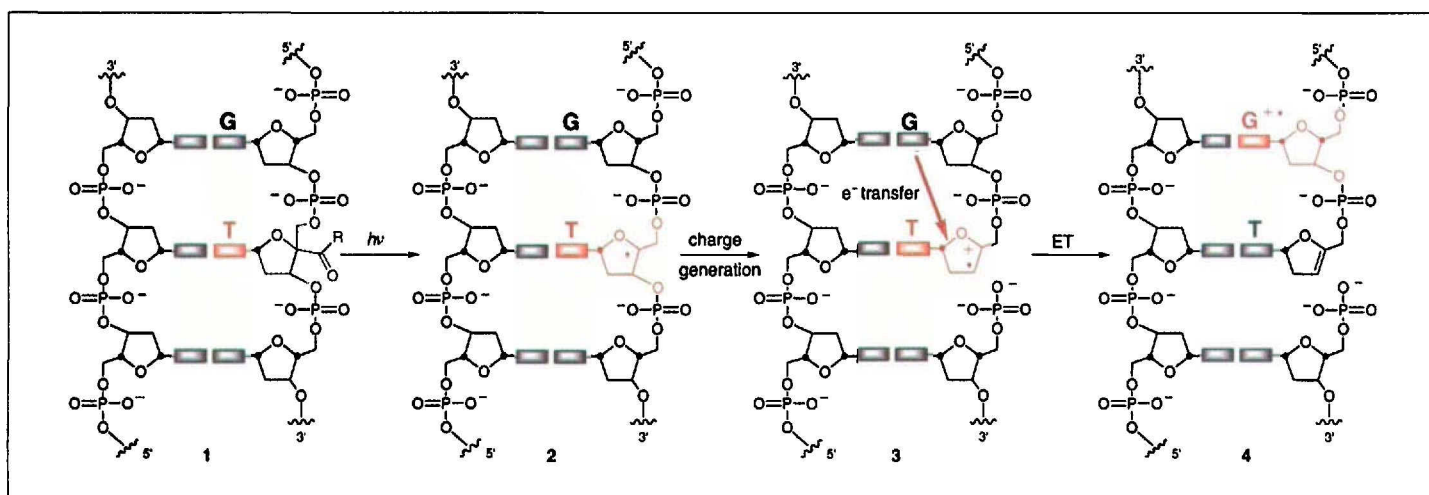
Scheme 1. Generation of the sugar radical cation **3** by photolysis of 4'-acylated DNA **1**. The sugar radical cation **3** can selectively oxidize an adjacent guanine (G) to a guanine radical cation **4**.
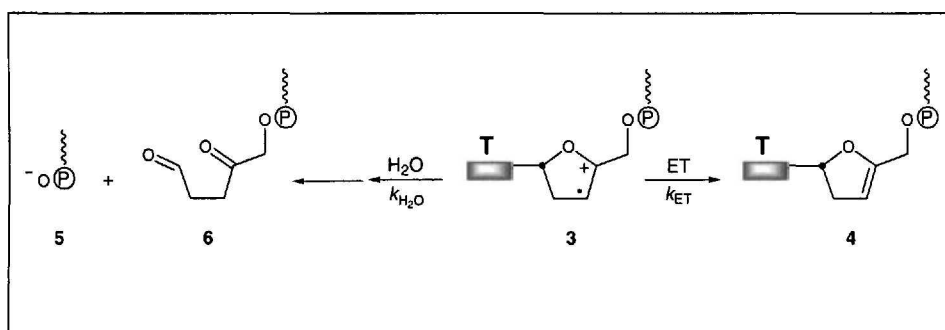
Scheme 2. Competition between H_2O and electron transfer (ET) reactions of the sugar radical cation **3**. The H_2O reaction leads to DNA cleavage products **5** and **6**, whereas the ET step yields enol ether **4**.

| X	G	9	A	T
enol ether **8** (%)	46	95	≤ 2	≤ 2
k_{ET} (s^{-1})	$0.9 \cdot 10^8$	$20 \cdot 10^8$	≤ $2 \cdot 10^6$	≤ $2 \cdot 10^6$

Scheme 3. Electron transfer (ET) from an adjacent base X to the sugar radical cation **7** leading to enol ether **8**. The yield of the enol ether **7** and the rate of the ET depend upon the base X.

This GGG sequence acts as a trap because its ionization potential is so low that in long A:T sequences most of the charge is trapped by H_2O before it can induce further charge transfer [3]. From the ratio of the cleavage products at the GGG sequence and the single G sites, the relative rates $k_{ET,rel}$ of the ET reactions were determined. As the data for charge transfer in double strands **13–16** demonstrate, the relative rates decreased by about a factor of 10 by increasing the length (Δr) of the bridge between the charge donor G$^{•+}$ and the GGG sequence by one AT base pair (Fig. 1).

According to the Marcus-Levich-Jortner Eqn. (a) this rate decrease leads to a β-value of 0.7 ± 0.1 Å^{-1} [3], which is identical to the β-value measured by Lewis, Wasielewski *et al.* [8] in direct kinetic measurements where the ET steps were initiated by a photoexcited stilbene.

$$\ln k \propto -\beta \cdot \Delta r \qquad (a)$$

These experiments clearly demonstrate that tunneling of electrons through DNA is strongly distance dependent, which should exclude very long distance charge transfer through DNA. But in ex-
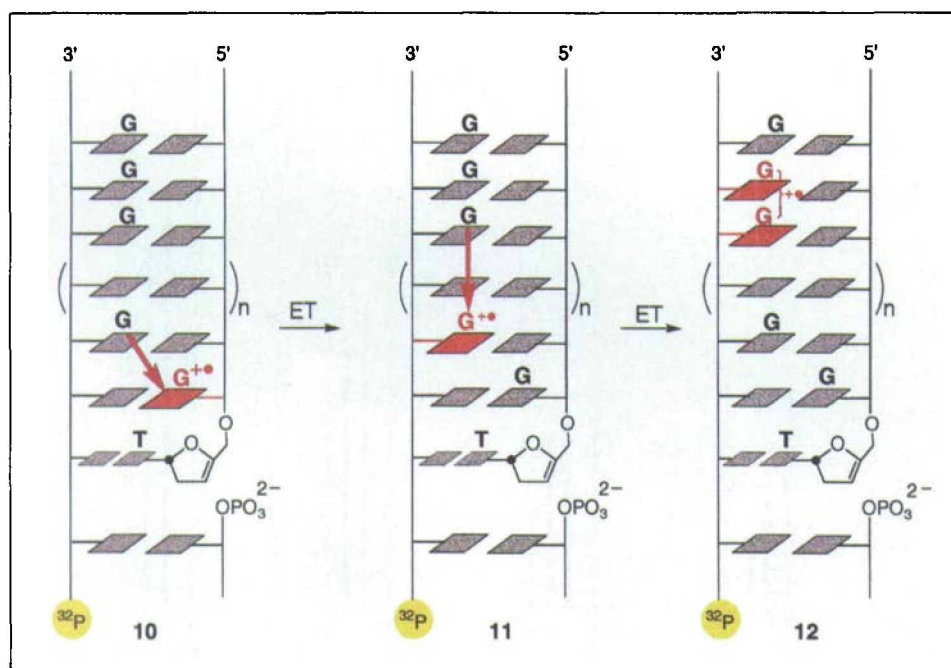
Scheme 4. Assay for the determination of the charge transfer from a guanine radical cation G•+ through a ³²P-radiolabeled DNA to a GGG sequence (11→12).
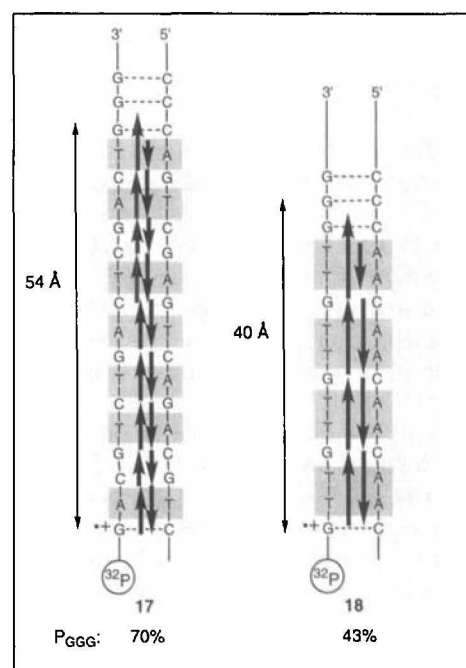

Fig. 2. Long-distance charge transport over 54 Å and 40 Å, respectively. The charge transport occurs by a hopping mechanism where the guanines (G) in the bridge between the charge donor G•+ and the charge acceptor GGG are relay stations for the charge. P_{GGG} is the yield of the charge trapped at the GGG charge acceptor.

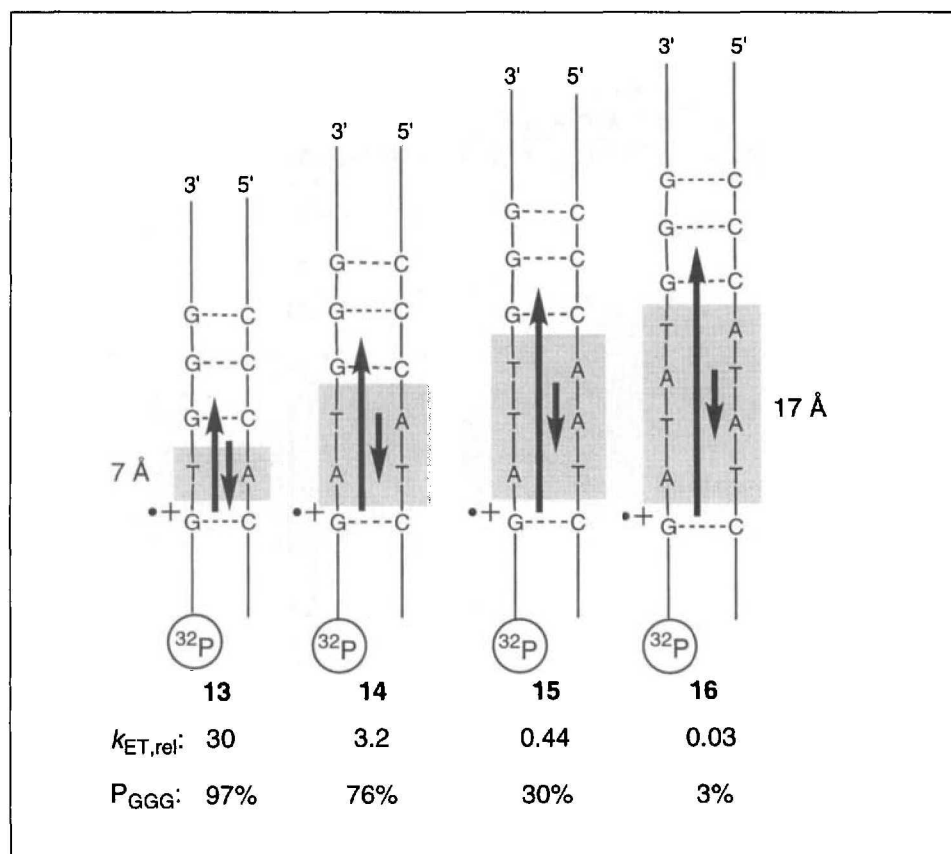Fig. 1. Distance dependence of the charge transfer step (tunneling) from a G•+ to a GGG sequence *via* a DNA bridge containing an increasing number of A:T base pairs. P_{GGG} is the yield of the charge trapped at the GGG charge acceptor by H_2O reaction and subsequent strand cleavage.

periments with double strands **17** and **18**, Meggers [3] and Wessely [9] demonstrated that the charge transport can be very efficient even if the charge donor and charge acceptor are separated from each other by a DNA bridge of more than 50 Å (Fig. 2).

This means that the charge transport depends not only on the distance but also on the DNA-sequence of the bridge. Strands **17** and **18** are different from strands **13–16** in that the bridge between G•+ and GGG does not contain only A:T but also G:C base pairs. In order to explain the effects, we suggested that the intermediate Gs are oxidized as the charge migrates from the donor G•+ to the acceptor GGG, so that the Gs act as relay stations for the positive charge [3]. According to this model the charge tunnels reversibly between the Gs until it is trapped by H_2O or the GGG sequence. Jortner *et al.* [10] has shown that such random walk of the charge is described by Eqn. (b) in which E is the efficiency of the charge transport, expressed by the ratio of trapped charge at the GGG sequence and at the single Gs. The number of the equidistant hopping steps is N.

$$\ln E \propto -\ln N \qquad (b)$$

We proved this Eqn. with strands **18–21** that have different numbers of 10 Å hopping steps [9] (Fig. 3).

The kinetic analysis of the multistep reactions of strands **18–21** showed that the ET rate for each 10 Å hopping step between $G^{•+}$ and a single G is much faster than the H_2O trapping reactions [11]. As a consequence, the charge should be distributed, after a short incubation time, over all Gs that are situated between the first $G^{•+}$ and the GGG sequence. This is actually the case as the chromatogram for DNA strand **18** shows [12] (Fig. 4).

The slow decrease of the yields with increasing distance to the charge injection site cannot be interpreted as a weak distance influence of the electron transfer rate because the rate determining step in the product formation is not the electron transfer rate but the trapping rate by H_2O. The slow decrease of the product yields show that at each hopping step from $G_1^{•+}$ *via* G_2 and G_3 to G_4 only a small portion of the charge is trapped irreversibly by H_2O so that the charge intensity only decreases slowly. This interpretation explains also the experiments of Schuster [5] and Barton and coworkers [13] on very long distance charge transfer through G-rich sequences of DNA (Fig. 5).

In strands **22** and **23** GG sequences are used as major relay stations and the yields of the cleavage products decrease very slowly with the distance to the charge injection site. The bridges between the GG sequences contain not only A:T but also G:C base pairs (Fig. 5). Because the charge transfer from $GG^{•+}$ to a single G is a very fast reaction, the single Gs can also act as relay stations. Thus, the charge migrates over the single Gs between the GG sequences. An appropriate description of the overall situation is given by the Curtin-Hammett picture shown in Fig. 6. In DNA strands containing very long A:T sequences, the charge transfer can also occur *via* adenine radical cations $(A^{•+})$ as charge carriers. The $A^{•+}$ is formed in a thermally activated equilibration of the charge in the GC sequence [14].

The results of my group as well as those from Schuster and Barton clearly demonstrate that a charge can travel through DNA over very long distances. The mechanism of this process now allows us to synthesize artificial DNA molecules where the competing H_2O reaction is even slower than in DNA itself. This should lead to new materials for nanoelectronic devices.
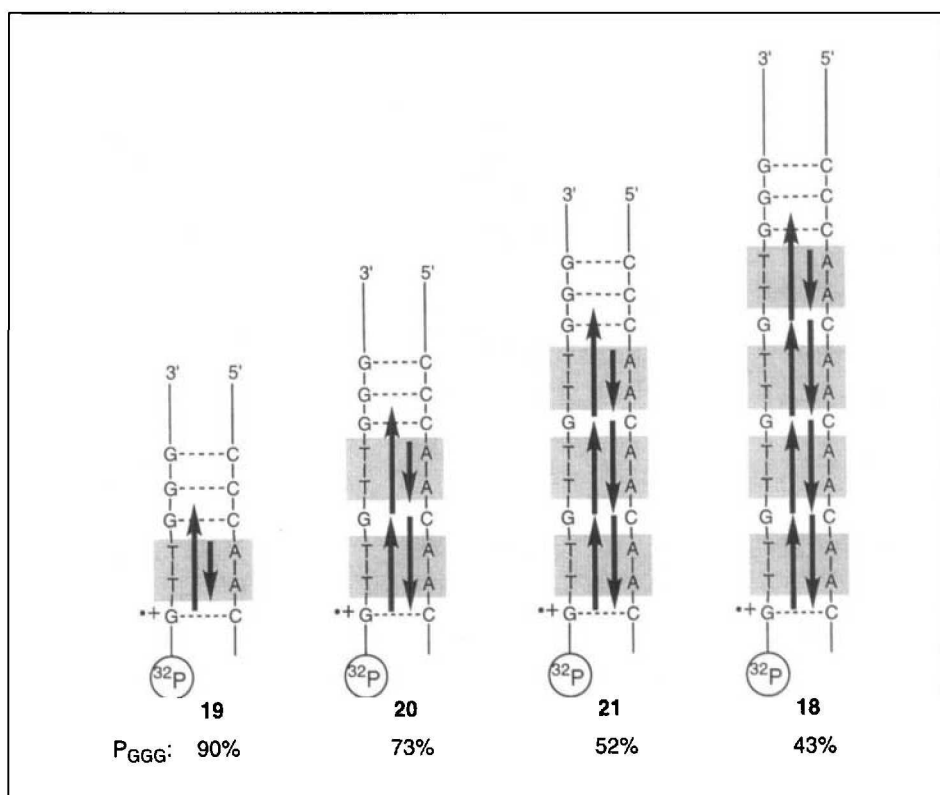

Fig. 3. Influence of the number of hopping steps on the efficiency of the charge transport. P_{GGG} is the yield of the charge trapped at the GGG charge acceptor.
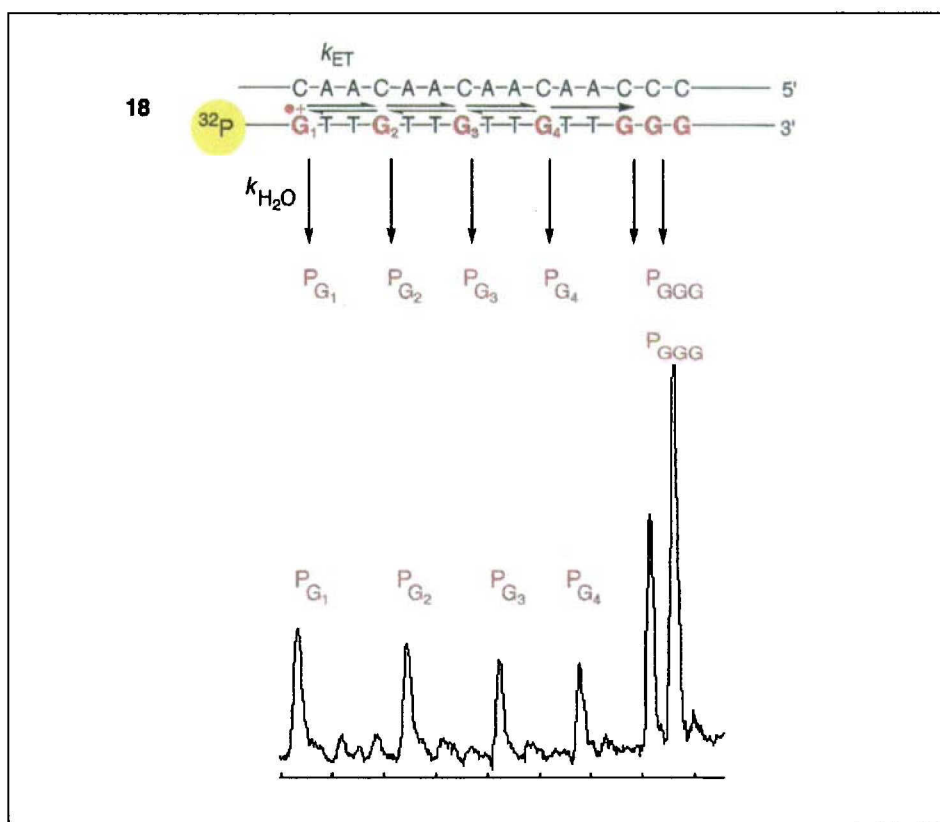

Fig. 4. Yield of the trapped charge at the relay stations G_1–G_4 between the charge donor $G_1^{•+}$ and the charge acceptor GGG. The chromatogram shows that the charge is distributed over all single Gs.
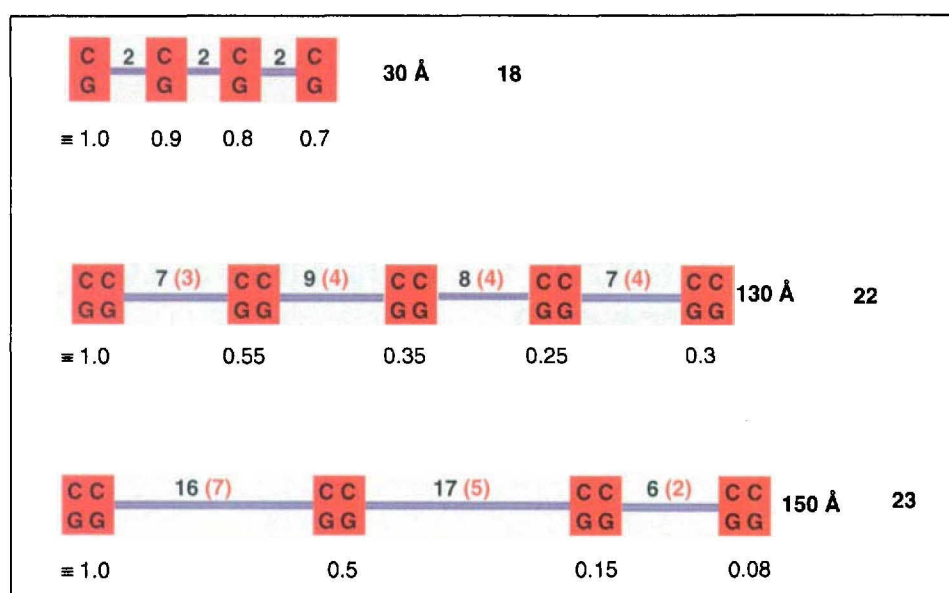
Fig. 5. Long-distance charge transport in strands **18**, **22**, and **23**. The numbers below the G or GG relay stations give the relative intensities of the charge trapped at these sites. The numbers over the bridges give the total number of base pairs in the bridge (in black) and the number of G:C base pairs (in red).
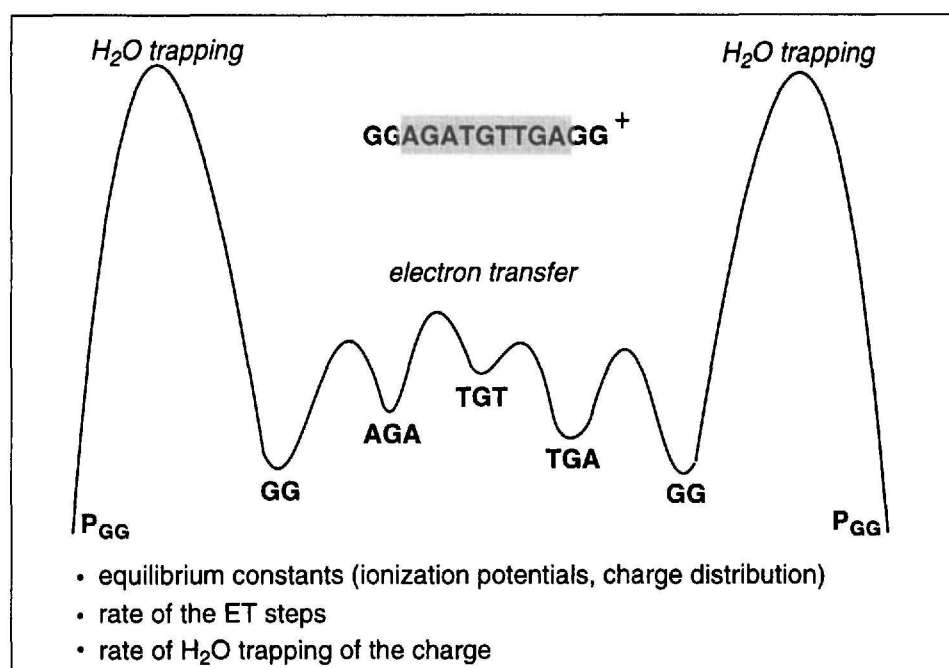

Fig. 6. Charge transport between two GG relay stations. The single Gs in the bridge also act as relay stations. Because of their higher ionization potentials, the concentration of the charge at the single Gs is so low that they are trapped only in very low yields. The yields of the products depend upon the electron transfer rates between the Gs and the H_2O trapping rates.

bases in order to increase the efficiencies of the long-distance charge transport. This should lead to modified DNA's as new materials for nanoelectronics.

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3. Conclusion

Long-distance charge transport through DNA is possible and this reaction occurs *via* a multistep hopping mechanism. If the ET hopping is faster than the H_2O trapping rate, the charge is distributed over the relay stations of the DNA bridge between the charge donor and the charge acceptor. The efficiency of the charge transport cannot be explained by the ET rates alone; the H_2O trapping reaction also plays an important role. Depending upon the base sequence which determines the nature and the number of the relay stations, as well as the bridge between the relay stations, the distance influence on the efficiency of the charge transport can be very weak or very strong. We are now modifying the