Programmable Quantitative DNA Nanothermometers

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ABSTRACT: Developing molecules, switches, probes or nanomaterials that are able to respond to specific temperature changes should prove of utility for several applications in nanotechnology. Here, we describe bioinspired strategies to design DNA thermostatic switches with programmable linear response ranges that can provide either a precise ultrasensitive response over a desired, small temperature interval (±0.05 °C) or an extended linear response over a wide temperature range (e.g., from 25 to 90 °C). Using structural modifications or inexpensive DNA stabilizers, we show that we can tune the transition midpoints of DNA thermometers from 30 to 85 °C. Using multimeric switch architectures, we are able to create ultrasensitive thermometers that display large quantitative fluorescence gains within small temperature variation (e.g., > 700% over 10 °C). Using a combination of thermoswitches of different stabilities or a mix of stabilizers of various strengths, we can create extended thermometers that respond linearly up to 50 °C in temperature range. Here, we demonstrate the reversibility, robustness, and efficiency of these programmable DNA thermometers by monitoring temperature change inside individual wells during polymerase chain reactions. We discuss the potential applications of these programmable DNA thermostatic switches in various nanotechnology fields including cell imaging, nanofluidics, nanomedicine, nanoelectronics, nanomaterial, and synthetic biology.

KEYWORDS: Nanothermometry, molecular switches, DNA nanotechnology, biosensors, PCR, fluorescence

Temperature is a key parameter, which controls the dynamic of all chemical, physical, and biological systems. With the advance of nanotechnology, it becomes imperative to develop tools that can precisely measure local temperature at the nanoscale. Such nanothermometers would prove useful in fields such as nanoelectronic,1 nanophotonics,2 microfluidics,3 and nanomedicine.4 A handful of thermostatic nanoswitches have been developed over the past decade. These include quantum dot nanocrystals,5 nanoparticle-based systems,6–8 nanogels,9,10 nanodiamonds,11 polymers,12,13 and proteins,14 and DNA-based thermostatic switches.15–17 These nanothermometers were applied to measure, for example, temperature variations in microfluidic devices9 and inside living cells.11,15 Despite these recent advances in nanothermometry, however, many drawbacks still limit the practicability and thus the usefulness of these approaches. These limitations include poor biocompatibility, low-temperature resolution, slow response time, complex synthesis, expensive instrumentation, low level of programmability, and complex nonlinear responses.18,19

Among the various nanothermometers described above, those working via a structure-switching mechanism12–17 represent a promising avenue. This is because these thermostatic switches can potentially be adapted to provide different signal readouts10 and can serve as building blocks to engineer more advanced thermostatic materials for applications such as drug delivery.21 Most specifically, switch-based nucleic acid thermostatic materials that are able to respond to specific signal changes should prove of utility for several applications in nanotechnology. Here, we describe bioinspired strategies to design DNA thermostatic switches with programmable linear response ranges that can provide either a precise ultrasensitive response over a desired, small temperature interval (±0.05 °C) or an extended linear response over a wide temperature range (e.g., from 25 to 90 °C). Using structural modifications or inexpensive DNA stabilizers, we show that we can tune the transition midpoints of DNA thermometers from 30 to 85 °C. Using multimeric switch architectures, we are able to create ultrasensitive thermostatic switches that display large quantitative fluorescence gains within small temperature variation (e.g., > 700% over 10 °C). Using a combination of thermostatic switches of different stabilities or a mix of stabilizers of various strengths, we can create extended thermometers that respond linearly up to 50 °C in temperature range. Here, we demonstrate the reversibility, robustness, and efficiency of these programmable DNA thermometers by monitoring temperature change inside individual wells during polymerase chain reactions. We discuss the potential applications of these programmable DNA thermostatic switches in various nanotechnology fields including cell imaging, nanofluidics, nanomedicine, nanoelectronics, nanomaterial, and synthetic biology.

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Figure 1. Bioinspired strategies to engineer programmable DNA-based nanothermometers. (a) Tuning the dynamic range of the nanothermometer by modifying the stability of the switch. (b) Tuning the dynamic range of the nanothermometer by adding an inexpensive, unlabeled allosteric DNA stabilizer strand. (c) Enhancing the signal gain (sensitivity) of the nanothermometer by engineering multimeric switch architectures. (d) Extending the dynamic range of the nanothermometer by combining switches (or stabilizers) with different stabilities.

Second, stem-loop thermometers only produce weak signal gains when measuring small temperature variations (e.g., 80°C and 35°C, fluorescence gain over a 10°C interval). This weak sensitivity precludes precise temperature sensing when only small temperature changes take place (e.g., ±1°C). Third, the fixed 12–15°C dynamic range limits the capacity of stem-loop thermometers to measure temperature variations spanning more than 15°C. In response to these limitations, we describe here various bioinspired strategies to engineer DNA thermostwiches with programmable sensitivities and dynamic ranges (Figure 1).

In order to shift the dynamic range of a DNA stem-loop so that it responds to different specific temperature variations, Jonstrup et al. have proposed to modulate the stem stability by changing either the buffer ionic strength (Figure S1) or the GC content of the stem (Figure 2a). By varying salt concentration (NaCl), we can tune the melting temperature (and thus the dynamic range) of the stem-loop switch by up to 30°C (Figure S1). However, changing the ionic strength may not be an option for tuning stem stabilities in applications such as in vivo temperature monitoring. Alternatively, DNA stem stability can also be modulated by substituting one AT base pair to a more stable GC base pair. For example, the melting transition of a 5-base pair stem-loop thermoswitch can be increased by roughly 10°C per AT to GC substitutions, going from 45 to 90°C (Figure 2a).

The main limitation of current DNA thermometers, however, is their inability to be tuned to respond to different temperature ranges. To overcome this, we propose here to employ a bioinspired allosteric regulation mechanism and re-engineer the DNA stem-loop so that it can be programmed to respond to many desired temperature windows via the addition of a simple, inexpensive DNA stabilizer (Figures 1b and 2b). For a DNA stem-loop switch, this is easily achieved by adding overhang DNA sequences at both extremities of the stem. A stabilizer can then be easily designed to bind these overhangs, which will stabilize the stem and shift the melting transition of the switch to higher temperatures (Figure 2b). Using DNA stabilizers of various lengths, we can tune the melting temperature and dynamic range of a single stem-loop switch by up to 30°C (~3.6°C on average per additional base on each side of the stabilizer) (Figure 2b inset). Another advantage of this stabilizer strategy is that it enables to tune “on-the-fly” the stability of a DNA stem-loops thermometer, and therefore its dynamic range, via the addition of a simple, inexpensive DNA strands to your experimental setup.

One promising feature of DNA-based thermometers is their fast response time, which is linked to the folding/unfolding rates of the DNA structures. In order to characterize the temporal resolution of the unimolecular (Figure 2a) and bimolecular (Figure 2b) stem-loops, we determined the folding/unfolding rates of these structures (Figure S2). Using rapid [NaCl]-jump experiments, we show that the unimolecular stem-loop folds and unfolds faster than the dead time of our mixing instrument (3.2 ms) as this has been previously observed for other similar DNA stem-loops. Although being significantly slower than its unimolecular counterpart, the bimolecular tunable stem-loop still provides a relatively rapid...
response time within a few seconds ($t_{1/2} \approx 0.08$ and 2 s for unfolding and folding, respectively at 45 °C) (Figure S2).

For some applications, the 12–15 °C unfolding dynamic range of the unimolecular stem-loop thermoswitch is too broad, thus limiting the ability to achieve sufficiently high signal gain when measuring small temperature changes. For example, stem-loop thermometers explored by Yang,15 Andersen,16 and Kompany-Zareh27 produce only 80, 35, and 250% fluorescence gain, over a 10 °C interval, respectively. This weak sensitivity reduces their usefulness in applications where only small temperature changes take place (±1 °C (e.g. in vivo imaging applications17)). In order to develop DNA switches with higher signal gain, we explored the unfolding transition of alternative more complex DNA folds, such as the DNA triplex helix, and the DNA G-quadruplex structure,26–28 hoping that they may display more cooperative melting transition (Figure S3). We found that both these DNA folds display a convenient single unfolding transition albeit with a sharper (triplex, 10 °C) and a more extended dynamic range (G-quadruplex, from 40 to 60 °C).

Inspired by the more cooperative melting behavior of the DNA triplex fold (Figure S3) and by the convenient properties of the tunable “allosteric” stem-loop (Figure 2b), we decided to combine both features into a single design in order to create an ultrasensitive, tunable, DNA thermometer. To do so, we exploited a DNA-clamp architecture29 in which a polypurine DNA strand is stabilized in a clamp conformation following its hybridization to a second polypyrimidine DNA strand via the formation of Watson–Crick and Hoogsteen interactions (see Material and Methods and ref 29). We find that the melting transition of this tunable DNA triplex clamp displays a much more cooperative transition (e.g., 3-fold larger fluorescence variation between 35 and 40 °C) with a linear dynamic range spanning less than 7 °C (Figure 3a, green dotted line). Notably, the triplex clamp switch also displays a lower background fluorescence (<10%) at low temperature thus enabling an unprecedented high signal gain over small temperature windows. For example, a comparable stem-loop thermometer (OGC) typically displays a 135% gain of fluorescence within the 30–40 °C interval (Figure 3a, black dotted line) while the tunable clamp switch displays a 710% gain of fluorescence in the same interval. This enables the DNA-clamp switch to detect temperature changes as small as 0.05 °C (Figure 3b and see Material and Methods for the determination of this precision).

In addition, we find that the melting transition of this tunable DNA clamp switch can be finely tuned from a 30 °C melting midpoint to an arbitrarily higher temperature through 2 °C increments by simply adding extra triplex-forming nucleotides in the stabilizer (Figure 3a, right inset). This highly sensitive DNA clamp switch, albeit with a limited dynamic range (7 °C), therefore represents an ideal nanothermometer to measure small temperature changes near biologically relevant temperatures (Figure 3b, right inset).

Encouraged by the ability of bimolecular switches (and other highly complex DNA structures) to provide steeper melting transitions (see also ref 28), we further explored the ability of multimeric DNA switches to display higher cooperative melting behavior (Figure 1c). We tested this idea by engineering a trimeric “triangle-like” DNA structure as well as a tetrameric “square-like” DNA structure (Figure S4). As expected, both these multimeric switches display a steeper melting transition compared to the unimolecular stem-loop thermoswitch with a dynamic range spanning only 7 °C (triangle) and 8 °C (square). Similarly to the triplex clamp switch, they also enable precise temperature measurement down to 28 °C. However, these tri- and tetra-molecular thermoswitches also possess a higher fluorescent background at low temperature (>15%), which reduces their gain and the amplitude of the fluorescence signal available in their linear dynamic range. Of note, these tri- and tetra-meric switches could prove useful to build thermosensitive switches where multiple elements could be associated or dissociated in function of small temperature variations.30

Another important limitation of DNA stem-loop thermometers is that their melting transitions do not span a dynamic range larger than 12–15 °C (Figure 2a). This fixed dynamic range limits their capacity to measure temperature variations spanning more than 15 °C. In order to extend the linear dynamic range of DNA thermometers so that they respond to greater temperature variations, we set out to combine individual thermoswitches, each displaying varying melting temperatures (Figure 1d) (see for analogy refs 29 and 31). For example, by combining six stem-loops with increasing GC contents in the stem (from OGC to 5GC), we are able to create a thermometer that displays a linear dynamic range spanning up to 48 °C (Figure 4a). Interestingly, such a mix of thermoswitches responds quite homogeneously to changes in sample condition (e.g., variation in salt concentration). For example, when the sensor is deployed at higher salt concentration this temperature sensor only shifts its dynamic range to higher temperature without affecting its range or linearity (Figure S5). Alternatively, by using our tunable stem-loop thermoswitch in combination with five unlabeled stabilizers of various lengths (18, 22, 24, 28, and 34 bases), we are also able to create a thermometer that displays a 46 °C wide dynamic range, similar...
Methods for switches and stabilizers (concentrations).

(a) Extending the dynamic range of DNA nanothermometers by combining switches with different stabilities (0GC, 1GC, 2GC, 3GC, 4GC, 5GC). (b) Extending the dynamic range of a single DNA stem-loops (Figure 4b see for analogy ref 32). Notably, this presents data points and red lines represent linear fits. All experiments were conducted using 25 nM of fluorescent labeled stem-loops in 50 mM NaPO₄ with 100 mM NaCl at pH 7.0 (see Material and Methods for switches and stabilizers concentrations).

Figure 4. Extending the dynamic range of DNA nanothermometers by combining thermoswitches or by adding a mix of DNA stabilizers. (a) Extending the dynamic range of DNA nanothermometers by combining switches with different stabilities (0GC, 1GC, 2GC, 3GC, 4GC, 5GC). (b) Extending the dynamic range of a single DNA thermoswitch by adding a collection of DNA stabilizers of different lengths (Stab_18, stab_22, stab_24, stab_28, stab_34). Black circles represent data points and red lines represent linear fits. All experiments were conducted using 25 nM of fluorescent labeled stem-loops in 50 mM NaPO₄ with 100 mM NaCl at pH 7.0 (see Material and Methods for switches and stabilizers concentrations).

to the extended thermometer made from a combination of 6 stem-loops (Figure 4b see for analogy ref 32). Notably, this “stabilizer” strategy significantly reduces the price of the extended thermometer from ~$1500 to roughly $300.

In order to illustrate the practicability and versatility of our programmable DNA thermometers, we employ them to monitor for the first time the temperature inside individual polymerase chain reactions (PCR) wells during several PCR cycles. To do so, we created a DNA thermometer that responds linearly within the temperature range of typical PCR experiments (i.e., from 45 to 93 °C) (Figure 4a). We first tested the reversibility of this fluorescent DNA thermometer by performing multiple, rapid temperature cycles over time (Figure 5a). This extended DNA thermometer (as well as other DNA thermometers, Figure S6) shows high reversibility over multiple cycles and displays high accuracy for temperature measurement when sufficient time is allowed for temperature equilibration. Interestingly, the thermometer also highlights a significant discrepancy between the block heater temperature and the temperature measured inside individual wells following rapid temperature jumps (Figure 5b). Because the stem-loop thermometer folds and unfolds faster than the millisecond time range (Figure S2), this observed equilibration time suggests that the sample inside each well may take several seconds before reaching the temperature indicated by the block heater (>10 s).

Figure 5. Real-time temperature monitoring in individual PCR wells using fluorescent DNA nanothermometers. (a) PCR cycles monitored using an “extended-range” thermometer that uses a combination of stem-loop thermoswitches (same stem-loop mix used than in Figure 2b). (b) Deviation between the PCR heating block temperature and the temperature measured inside individual wells using the fluorescent DNA nanothermometer (zoom from panel a). (c,d) Temperature equilibration rates inside a PCR well following rapid temperature jumps (1.35 °C/s) as monitored using two different DNA thermoswitches. In red, a 3GC stem-loop; in green, a stem-loop stabilized with a 34-nucleotide stabilizer (panel c) or a 30-nucleotide stabilizer (panel d). Temperature equilibration rates were found to be 0.14 and 0.13 s⁻¹ while heating and 0.17 and 0.19 s⁻¹ while cooling with the 3GC and stabilizer-tuned stem-loops thermometers, respectively. The small upward deviation (0.5 °C) observed for the stem-loop-stabilized thermometer in panel d is attributable to the limited linear dynamic range of this thermometer. Experiments were performed using 150 nM of mixed thermoswitches (panels a,b) in 50 mM Na₂HPO₄ and 300 mM NaCl at pH 7.0 or 50 nM of stem-loop (panels c,d) with 200 nM of stabilizer for the stabilizer-stem-loop thermometer in 50 mM Na₂HPO₄ with 100 mM NaCl at pH 7.0.

In order to precisely measure this equilibration time, we performed rapid 10 °C temperature jumps (i.e., 60 to 70 °C and 70 to 60 °C in 7.4 s) while monitoring sample temperature using two different thermometers with optimal sensitivity for this temperature range (a 3GC stem-loop and a stabilizer-tuned stem-loop) (Figure 5c,d). Temperature equilibration rates inside PCR wells were found to be 0.14 and 0.13 s⁻¹ while heating and 0.17 and 0.19 s⁻¹ while cooling when using the unimolecular 3GC and the stabilizer-tuned stem-loops thermometers, respectively. These results suggest that the sample temperature inside a PCR well only reaches the block heater temperature (±1 °C) 15 s after the block heater has reached it. Overall, this implies that sufficient equilibration time should be taken into consideration when using PCR instruments for quantitative purposes that require precise sample temperature measurements. For instance, DSF experiments, which are employed to determine the strength of molecule–protein interactions, will overestimate the affinity if PCR melting transitions are performed too rapidly.

Here, we have engineered several DNA-based thermometers with programmable quantitative, linear dynamic ranges for optimal temperature monitoring at the nanoscale. More specifically, we have introduced various design strategies to tune “on-the-fly” the melting transition temperature and the cooperativity of
folding/unfolding transitions of these thermoswitches. Through structural modifications of the thermoswitch or via addition of inexpensive DNA stabilizers, we demonstrated that we can tune the transition midpoint from 30 to 85 °C. Through multimeric and triplex clamp switch architectures, we increased the thermoswitch sensitivity and created high gain thermoswitch that displays ~3-fold higher signal gain then stem-loop thermometers. Through a combination of thermoswitches or via addition of a combination of inexpensive DNA stabilizers, we demonstrated that we can extend the linear, quantitative, relations,55−57 which may help to optimize treatment. The DNA thermoswitches could be incorporated into larger, drug carrying, structures,37 or in nano- or microfluidic devices where local temperature at nanoscale may be of crucial importance.38 These switches could also be attached to metal nanoparticles in order to accurately sense small temperature variations during laser-based nanosurgery59 or magnetic hyperthermia treatments,60 may help to optimize treatment. The DNA thermoswitches could also be adapted in an electrochemical format,41 and find applications in microfluidic devices such as point-of-care PCR instruments42 which require multiple precise temperature settings despite external variations. Electrochemical DNA thermoswitches may also find applications in nano-electronics to detect hotspots caused by defects in nanometric circuits.43 Finally, these programmable DNA thermoswitches could be used to build thermosensitive structures that may find applications in the field of DNA nanomachines,44 drug delivery systems,45 and macromolecular assemblies.35 For example, thermoswitches could be incorporated into larger, drug carrying, DNA devices46−48 in order to create thermally responsive systems that deliver their cargo via local temperature changes using either bodily temperature gradients or laser-induced heating.49,50 Finally, these DNA thermosensitive structures could also inspire the design of thermally responsive RNA strands that could be genetically encoded in mRNA to reprogram gene expression so that it is induced at various specific temperatures.51,52

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nanolett.6b00156.

Material and Methods and supplementary figures. (PDF)
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