BDNF modulates heart contraction force and long-term homeostasis through truncated TrkB.T1 receptor activation

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Brain-derived neurotrophic factor (BDNF) is critical for mammalian development and plasticity of neuronal circuitries affecting memory, mood, anxiety, pain sensitivity, and energy homeostasis. Here we report a novel unexpected role of BDNF in regulating the cardiac contraction force independent of the nervous system innervation. This function is mediated by the truncated TrkB.T1 receptor expressed in cardiomyocytes. Loss of TrkB.T1 in these cells impairs calcium signaling and causes cardiomyopathy. TrkB.T1 is activated by BDNF produced by cardiomyocytes, suggesting an autocrine/paracrine loop. These findings unveil a novel signaling mechanism in the heart that is activated by BDNF and provide evidence for a global role of this neurotrophin in the homeostasis of the organism by signaling through different TrkB receptor isoforms.

Introduction

Brain-derived neurotrophic factor (BDNF) is a growth factor widely expressed in the nervous system. Changes in its level have been found and correlated to the development of several human diseases including neurodegeneration, depression, psychiatric disorders, and obesity (Chao et al., 2006; Nagahara and Tuszynski, 2011; Lu et al., 2014). The direct relevance of normal BDNF signaling to human fitness has been validated by the use of animal models, which have also allowed the dissection of the molecular mechanism underlying BDNF function in vivo (Rios et al., 2001; Zuccato and Cattaneo, 2009; Baydyyuk and Xu, 2014). The TrkB gene encodes BDNF high affinity receptors that are widely expressed in neuronal tissues (Klein et al., 1990; Escandón et al., 1994). This locus generates multiple TrkB isoforms all of which have the same extracellular domain but have different intracellular domains (Stoilov et al., 2002). The two main isoforms include a full-length receptor with a tyrosine kinase domain (TrkB.Kin) used for signaling and a truncated TrkB.T1 receptor lacking kinase activity (Klein et al., 1990; Dorsey et al., 2006). Although a role for TrkB.Kin has been established in neuronal development and function including differentiation, outgrowth, and synaptic plasticity, the physiological significance of TrkB.T1 intrinsic signaling is still unclear despite its high sequence conservation among species and its being the most highly expressed TrkB isoform in the mature animal. Mice lacking TrkB.T1 have increased anxiety-related behavior that is associated with structural alterations in neurites of the amygdala (Carim-Todd et al., 2009). Despite reports of TrkB.T1 signaling in isolated glia cells there are no obvious deficiencies in this cell population in TrkB.T1 mutant mice (Rose et al., 2003; Dorsley et al., 2006; Ohira et al., 2006; Carim-Todd et al., 2009). In the cardiovascular system, BDNF and its receptor TrkB have been described to have an early developmental role in cardiac endothelium formation (Anastasia et al., 2014). Interestingly, in the adult heart only TrkB.T1-specific polyadenylated mRNA has been reported, suggesting protein expression of this particular receptor isoform (Stoilov et al., 2002). Our analysis confirms this finding and we further show that it mediates BDNF inotropic function by regulating Ca2+ signaling. We found that specific deletion of TrkB.T1 in cardiomyocytes causes cardiomyopathy and that BDNF is the ligand activating TrkB.T1. We show that BDNF is secreted by cardiomyocytes and its specific deletion in cardiomyocytes causes a cardiomyopathy resembling that caused by TrkB.T1 deficiency. Our data unveil a novel nonneuronal function for BDNF and uncover the first physiologically relevant direct signaling activity of the TrkB.T1 receptor. These findings identify a new pathway regulating cardiac contractility and suggest that perturbation in BDNF and TrkB expression may cause cardiac pathological conditions.

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Results

To address a potential role of BDNF in the mature cardiovascular system we first investigated the pattern of expression of its receptor TrkB in the adult mouse heart (Fig. 1). Although the full-length TrkB tyrosine kinase receptor is expressed in the cardiac endothelium during development (Donovan et al., 2000), we found that in the adult this isoform is virtually undetectable and only trace levels of its mRNA can be found by RT-PCR (Fig. 1, B and C). Instead, truncated TrkB.T1 protein is the dominant cardiac-expressed isoform as previously shown by RNA expression analyses (Fig. 1; Stoiilov et al., 2002). The presence of TrkB mRNA and protein in the heart suggests an intrinsic role for this receptor independent of the nervous system. (A) Western blot analysis of brain, heart, and cardiomyocyte lysates from adult WT and TrkB.T1-deficient (T1−/−) mice. Lysates were incubated with wheat germ lectin agarose to enrich for glycoproteins. The wheat germ agglutinated (WGA) precipitates were analyzed by Western blot analysis with an antibody directed against the extracellular domain of TrkB to detect all TrkB isoforms. Note that in whole heart and cardiomyocytes (Cardio) only a truncated TrkB isoform (80–90 Kd) is detected. The absence of the corresponding band in the TrkB.T1 knockout animals verifies the identity of the receptor. Brain lysates were used as a positive control. Right panel, input lysates. (B) Quantification of real-time PCR analysis as expressed by the number of PCR cycles at which full-length TrkB (TrkB.Kin) or TrkB.T1-specific PCR products are equal to GAPDH level (Δ Ct) from total cardiomyocyte RNA. Note that TrkB.T1 is expressed at a much higher level as PCR products appear after only 5 cycles of GAPDH detection versus 11 cycles for TrkB.Kin. (C) Ethidium bromide agarose gel visualizing the size of the DNA fragments from heart RT-PCR analysis. Note that the size of the PCR reaction products corresponding to TrkB kinase [Kin] and TrkB.T1 [T1] are the same as those from brain used as a positive control. B, brain; H, heart.

The fast action of BDNF and the finding that K252a does not block the BDNF inotropic effect but was instead additive, suggesting that BDNF signaling does not overlap with the catecholamine pathways (Fig. 3, A and B). In addition, when we tested whether BDNF changes the phosphorylation level of some of the major molecular players involved in cardiac contraction, including CamKII, phospholamban (PLB), and troponin, we found that in Langendorff-perfused hearts at the peak of BDNF action phosphorylation levels were unchanged contrary to hearts treated with forskolin used as positive control (Fig. 3, C–F). These data suggest that BDNF exerts cardiac function through other pathways or this effect is modulatory and not immediately detectable with conventional biochemical analysis.

The effect on cardiac contraction force suggests that cardiomyocytes may be the cell type responding to BDNF with Ca2+ as the possible downstream effector. Therefore, we tested adult cardiomyocytes for TrkB expression and their response to BDNF (Fig. 1 A and Fig. 2, I–K). We found that isolated cardiomyocytes do express TrkB.T1 (Fig. 1 A) and when subjected to direct depolarization they elicited higher Ca2+ transients by treatment with BDNF compared with just vehicle (Fig. 2 I). Moreover, the Ca2+ transient increase was reversible because it was restored to the basal electrical stimulation level after BDNF removal (Fig. 2 J).

The fast action of BDNF and the finding that K252a does not block this function in heart (Fig. 2 B) and cardiomyocytes (Fig. 2 K) suggest that this role is not mediated by the TrkB ki-
Figure 2. *TrkB.T1 mediates BDNF-induced acute increase in cardiac contraction force and calcium transient increase evoked by direct stimulation in cardiomyocytes.* (A and B) BDNF (1 ng in 50 µl Krebs solution) injected in the fluid streamline of a Langendorff-perfused mouse heart induces an increase in systolic pressure and a consequent decrease of the diastolic pressure (A) that is not affected by the TrkB kinase inhibitor K252a (B). Arrows indicate the time of BDNF injection and the broken line (B) indicates K252a presence throughout the 80-s duration of the experiment. (C) Representative traces showing the changes in LVDP before (baseline) and after BDNF injection. (D) Representative traces showing the increase in LVPD caused by BDNF in WT (E) but not in *TrkB.T1* knockout (T1<sup>−/−</sup>; F) hearts. A bolus of 50 µl of 5 mM caffeine in Krebs solution was injected 5 min after BDNF as a positive control. The BDNF and caffeine traces were overlapped using the injection time as the starting point (arrow). Note the lack of LVPD change in response to BDNF in the *TrkB.T1* mutant mouse despite normal response to caffeine. (G and H) Quantification of data in E and F showing the percent change of baseline LVPD in response to BDNF (G) and caffeine (H) in WT and T1<sup>−/−</sup> hearts. (I) Representative traces of Ca<sup>2+</sup> transients elicited by 2-Hz stimulation in isolated adult cardiomyocytes. Ca<sup>2+</sup> transients are increased by BDNF application only in WT (BDNF, light gray; no BDNF, black) but not in T1<sup>−/−</sup> cardiomyocytes. (J) Effect of BDNF on transient amplitude is reversible as shown in typical time course from a WT and a T1<sup>−/−</sup> cardiomyocyte. BDNF effect on Ca<sup>2+</sup> release has a rapid onset and is completely reversed in <2 min upon BDNF removal. (K) Quantification of peak amplitude of calcium transient in WT and T1<sup>−/−</sup> cardiomyocytes. The value for each group represents the transient change in percentage before (considered as 100%) and after BDNF application. 10 transients before and 10 transients after BDNF application were measured for each cardiomyocyte analyzed (n is shown within the bar). Values in G–K are indicated as the mean ± SEM. *, P < 0.05.

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Figure 2. *TrkB.T1 mediates BDNF-induced acute increase in cardiac contraction force and calcium transient increase evoked by direct stimulation in cardiomyocytes.* (A and B) BDNF (1 ng in 50 µl Krebs solution) injected in the fluid streamline of a Langendorff-perfused mouse heart induces an increase in systolic pressure and a consequent decrease of the diastolic pressure (A) that is not affected by the TrkB kinase inhibitor K252a (B). Arrows indicate the time of BDNF injection and the broken line (B) indicates K252a presence throughout the 80-s duration of the experiment. (C) Representative traces showing the changes in LVDP before (baseline) and after BDNF injection. (D) Representative traces showing the increase in LVPD caused by BDNF in WT (E) but not in *TrkB.T1* knockout (T1<sup>−/−</sup>; F) hearts. A bolus of 50 µl of 5 mM caffeine in Krebs solution was injected 5 min after BDNF as a positive control. The BDNF and caffeine traces were overlapped using the injection time as the starting point (arrow). Note the lack of LVPD change in response to BDNF in the *TrkB.T1* mutant mouse despite normal response to caffeine. (G and H) Quantification of data in E and F showing the percent change of baseline LVPD in response to BDNF (G) and caffeine (H) in WT and T1<sup>−/−</sup> hearts. (I) Representative traces of Ca<sup>2+</sup> transients elicited by 2-Hz stimulation in isolated adult cardiomyocytes. Ca<sup>2+</sup> transients are increased by BDNF application only in WT (BDNF, light gray; no BDNF, black) but not in T1<sup>−/−</sup> cardiomyocytes. (J) Effect of BDNF on transient amplitude is reversible as shown in typical time course from a WT and a T1<sup>−/−</sup> cardiomyocyte. BDNF effect on Ca<sup>2+</sup> release has a rapid onset and is completely reversed in <2 min upon BDNF removal. (K) Quantification of peak amplitude of calcium transient in WT and T1<sup>−/−</sup> cardiomyocytes. The value for each group represents the transient change in percentage before (considered as 100%) and after BDNF application. 10 transients before and 10 transients after BDNF application were measured for each cardiomyocyte analyzed (n is shown within the bar). Values in G–K are indicated as the mean ± SEM. *, P < 0.05.

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BDNF signals independently of the catecholaminergic pathway and does not increase cardiac CamKII or PLB phosphorylation at the peak of its inotropic function. (A) Isoproterenol does not occlude the effect of BDNF in Langendorff-perfused hearts. Representative LVDP trace obtained from application of 100 nM isoproterenol (ISO) to a Langendorff-perfused heart. Once the heart reached stable LVDP a 50 µl (10 ng total) bolus of BDNF was applied followed by a second 50 µl (5 mM) bolus of caffeine as a positive control 2 min later. (B) Quantification of the effect of BDNF and caffeine on baseline LVDP in the absence or presence of ISO. The baseline for the values obtained with ISO is considered LVDP in the presence of ISO. Values are from four independent experiments. (C–F) BDNF does not increase cardiac CamKII or PLB phosphorylation at the peak of its inotropic function. (C) Western blot analysis of PLB phosphorylation at Ser16 (PLB P-S16) and Thr17 (PLB P-T17), CAMKII phosphorylation at Thr 286/287 (CAMKII P-S286), and Troponin I at Ser23/24. Langendorff-perfused hearts were injected with vehicle (negative control), BDNF, or Forskolin (positive control) as described in Material and methods. (D–F) Quantification of the bands intensity ±SEM from C reported as the ratio between the phosphorylated form over the specific total protein. Means of the three samples ±SEM are shown. * P < 0.05, calculated with two-tail t test.
from two- to three-month-old Myh6-cre-BDNF knockout mice showed dilated cardiomyopathy with significantly reduced posterior wall thickness compared with littermate controls (Fig. 5, G–K). Strikingly, the similarity between the phenotype observed in Myh6-cre-BDNF– and Myh6-cre-TrkB.T1–deficient mice suggests that BDNF-TrkB.T1 signal is intrinsic to cardiomyocytes and functions by an autocrine/paracrine mechanism.

**Discussion**

We have identified a new unexpected role of BDNF in adult cardiac physiology. This action is mediated by truncated TrkB.T1 receptors expressed in cardiomyocytes and is independent of BDNF function in the nervous system. Although truncated TrkB.T1 has an intracellular domain that is extremely conserved among species, so far there is no data suggesting physiological relevance of its direct signaling in vivo. In isolated glial cells, TrkB.T1 evokes Ca²⁺ signal, but mice lacking this receptor do not show any obvious defect in this cell population (Carim-Todd et al., 2009). The lack of a phenotype could be a result of compensatory mechanisms, redundancy of TrkB.T1-mediated Ca²⁺ signaling in this cell type, or a function required during specific physiological challenges. However, we found that in cardiomyocytes Ca²⁺ regulation by TrkB.T1 is critical as deletion of this receptor causes dilated cardiomyopathy. BDNF activation of TrkB.T1 appears modulatory of cardiac function as in a Langendorff-perfused heart it causes only a 5% increase in cardiac contraction force; yet loss of this pathway leads to cardiomyopathy over the life of the animal. Indeed, it is not surprising that even small perturbations in the proper control of Ca²⁺ levels are deleterious to normal cardiac function as Ca²⁺ regulation is central to the function of cardiomyocytes. Moreover, we provide evidence that BDNF is the ligand activating TrkB.T1 in an autocrine/paracrine fashion as it is expressed and released by cardiomyocytes and its deletion in this cell type causes a cardiomyopathy resembling that caused by TrkB.T1 knockout. Most recently, a parallel study has suggested that TrkB is required for normal cardiac contraction and relaxation (Feng et al., 2015). Contrary to our study that shows that TrkB.T1 is the receptor for BDNF in the heart, Feng et al. (2015) suggested that instead this function is mediated by the TrkB kinase
receptor isoform. This finding is somewhat surprising because we and others have found that in the heart TrkB.T1-encoding mRNA is highest, whereas the TrkB kinase messenger RNA is virtually undetectable (Stoilov et al., 2002). The discrepancies in protein analysis data can be explained by the use of different antibodies and appropriate controls. Nevertheless, the most important difference relates to the cardiac phenotype observed by Feng et al. (2015) in mouse models with specific inactivation of the kinase domain either by a chemical genetic (i.e., the TrkB.F616A/1-NMPP1 model) or by a conditional deletion approach. We found that in Langendorff-perfused WT mouse hearts 100 nM 1-NMPP1 induced a dramatic increase in the cardiac contraction force and blunted the BDNF effect. Although Feng et al. (2015) reported that 1-NMPP1 did not alter basal cardiomyocyte function they did not include a control to test whether 1-NMPP1 blunts BDNF action as we found (Fig. S3). Thus, it is possible that such an omission leads to misinterpreting the lack of BDNF inotropic function within the context.

Although, we do not have a definitive explanation for the results obtained with a conditional deletion of a TrkB tyrosine kinase–specific exon, it has been reported that targeting the kinase domain of TrkB causes a dramatic down-regulation of the TrkB.T1 isoform protein (Klein et al., 1993). Although Klein et al. (1993) had no explanation for the disregulation, this finding suggests the possibility that a similar targeting of the kinase region by Feng et al. (2015) generates a TrkB.T1 hypomorph. In support of this scenario is the fact that targeting of the kinase domain causes only reduced systolic function insufficient to trigger chamber dilation (Feng et al., 2015), whereas the complete deletion of TrkB.T1 achieved in our study causes a more severe pathology that includes cardiac dilation developed as a consequence of impaired Ca²⁺ signaling. Importantly, targeting of the TrkB.T1-specific exon does not cause changes in the expression of the TrkB kinase receptor, again suggesting specificity of the phenotype (Fig. 1; Dorsey et al., 2006). Nevertheless, the study by Feng et al. (2015) is important because it supports the finding that TrkB has an intrinsic role in cardiomyocyte function that is independent of cardiac innervation. Moreover, despite the possible explanations for the discrepancies between the two analyses, we cannot entirely exclude that a very small level of the TrkB tyrosine kinase receptor may in part be responsible for the BDNF effect in the heart.
An important new contribution of our study relates to the fact that we have identified the source and identity of the neurotrophin activating TrkB.T1 in the heart. This is relevant because other neurotrophins expressed in the heart could be responsible for this function (Scarabelli et al., 1993; Emanueli et al., 2014). Moreover, our data suggest that BDNF produced in loco is a significant determinant of TrkB.T1 cardiac function. This was even more surprising considering the relatively low level of BDNF present in the heart compared with the brain (only ~5% per gram of tissue; Fig. 6 A). In the future it will be of interest to investigate whether BDNF produced by peripheral districts (i.e., striatal muscle) can affect cardiac function and whether loss of either cardiac or peripheral BDNF is sufficient to cause cardiomyopathy.

A major question still unresolved relates to how TrkB.T1 transduces BDNF inotropic function. The fact that the BDNF effect is additive to that of isoproterenol, a nonselective β-adrenergic agonist, suggests that BDNF signaling does not overlap with the catecholamine-activated pathway. Moreover, in an initial analysis of some of the key players in cardiac excitation–contraction coupling, including CamKII, PLB, and troponin I, we found no changes in their level of activation in response to BDNF treatment. This result appears to contrast the finding by Feng et al. (2015) that BDNF increases PLB, CamKII, and RyR receptor phosphorylation. However, their result was obtained after a prolonged treatment (10 or 20 min) of cardiomyocytes with BDNF, raising the possibility that the increase in the phosphorylation of these excitation–contraction coupling players may be secondary because it is detected after BDNF inotropic effect has already subsided. In our paradigm we found that at the peak of BDNF inotropic function in Langendorff-perfused hearts there was no increase of PLB or CamKII phosphorylation, suggesting that they are not directly involved in BDNF contraction in cardiomyocytes.

In glia cells TrkB.T1 mediates inositol-1,4,5-trisphosphate (IP₃)-dependent calcium release from intracellular stores. It was proposed that this mechanism involves an as yet unidentified G protein that stimulates PLC production of IP₃, Ca²⁺ release from stores, and Ca²⁺ entry from the extracellular space. It is tempting to speculate that a similar mechanism is at work in cardiomyocytes where TrkB.T1 induces Ca²⁺ release from the intracellular stores and increases systolic Ca²⁺ transients (Fig. 2). Indeed, IP₃ can contribute to systolic Ca²⁺ transients through a mechanism by which IP₃ receptors are opened by a combination of IP₃ and Ca²⁺ binding (Missiaen et al., 1994; Bootman et al., 1995). According to such a model, IP₃ receptors can sit with IP₃ bound and wait for an activating Ca²⁺ signal to derive from voltage-activated channels or neighboring RyRs (Kockskämper et al., 2008). In turn, activated IP₃ receptors would cause further release of Ca²⁺ from the ER, increasing the systolic Ca²⁺ transients. Importantly, several studies point toward a relevant role of PLC–IP₃ signaling in the development and progression of cardiac hypertrophy and dilation, further supporting a link of BDNF to this pathway (Mende et al., 1998; Kockskämper et al., 2008). In the future, it will be important to investigate through pharmacological and genetics approaches whether this is indeed the TrkB.T1-activated pathway in cardiomyocytes.

Lastly, considering the importance of BDNF/TrkB signaling in the control of food intake, mood disorders, and neurodegenerative diseases there is a significant effort to develop pharmacological agents to harness the activation of this pathway (Nagahara and Tusznyski, 2011; Lu et al., 2014). Although most studies have been focused on the generation of BDNF mimetic molecules, which can activate all TrkB receptors (Longo and Massa, 2013; Rosenthal and Lin, 2014), the present results suggest that any such effort should consider possible effects on the function of the cardiovascular system. Nevertheless, our data indicate that pharmacological activation of intracellularly activated TrkB kinase pathways such as by a transactivation mechanism may achieve central nervous system activation of TrkB kinase without causing cardiac toxicity (Wiese et al., 2007; Yanpallewar et al., 2012).

**Materials and methods**

**Mouse models**

TrkB.T1 knockout and conditional mutant mice were generated as described previously (Dorssey et al., 2006). BDNF-HA mice (Yang et al., 2009) were a gift of B. Hempstead (Cornell University, New York, NY). BDNF conditional (Rios et al., 2001) mutants as well as Myh6-cre (Agah et al., 1997) and Cadherin5-cre (Alva et al., 2006) transgenic...
mice were obtained from the Jackson Laboratory. The Rosa26loxPdLacZ mouse (strain 003474; The Jackson Laboratory) was used as a Cre reporter strain to test the tissue/cellular expression pattern of cre transgenic animals. Animals were bred in a specific, pathogen-free facility with food and water ad libitum. All experimental procedures followed the National Institutes of Health guidelines for animal care and use and were approved by the National Cancer Institute at Frederick Animal Care and Use Committee.

**Western blot analysis**

Mouse hearts were quickly dissected and washed in cold PBS. After removal of the atria, ventricles were lysed in a Precellys ceramic lysing kit tube with 1 ml RIPA buffer by two 30-s cycles at 5,000 rpm in PRECELLYS 24 (Bertin Technologies). Ventricle or adult cardiomyocyte lysates (see the Adult mouse cardiomyocyte isolation section) were then incubated with wheat germ agglutinin–agarose beads in RIPA buffer for 4 h at 4°C. Beads were washed three times with RIPA buffer, resuspended in Laemmli sample buffer, and boiled for 5 min before loading in 4–12% NuPAGE (Life Technologies) precast gels for Western analysis. For the analysis of CamKII, PLB, and Troponin I, hearts were perfused in a Langendorff apparatus as described in the Langendorff heart preparation section with a modified Krebs solution with or without 20 ng/ml BDNF (PeproTech) or 5 µM Forskolin (Sigma-Aldrich) used as a positive control. Heart contractility was monitored during the perfusion process and at the peak of cardiac pressure induced by BDNF or Forskolin the hearts were snap frozen with stainless steel clamps cooled in liquid nitrogen and stored frozen before homogenization in RIPA buffer supplemented with proteases (complete mini; Roche) and phosphatase inhibitors (PhosSTOP; Roche). Lysates were centrifuged at 15,000 g for 15 min at 4°C and the supernatants were diluted in 2x Laemmli sample buffer, boiled, and loaded in a gel for Western analysis. Membranes (PVDF; Life Technologies) were blocked in 5% nonfat milk or 5% BSA in TBS-Tween before incubation with a specific antibody. Antibodies were as follows: anti-TrkB (against the extracellular domain of TrkB and therefore recognizing all TrkB isoforms; EMD Millipore), anti-TrkB.T1 (Santa Cruz Biotechnology, Inc.), anti-GAPDH (EMD Millipore), anti-Cal c (L-Type calcium channel subunit a1c; Alomone Labs), anti-HA (for Western; Covance; for immunoprecipitation, Sigma-Aldrich), anti-Phospho-TrkB raised against phosphorylated TrkB-Tyr516 (Cell Signaling Technology), anti–total CAMKII (Cell Signaling Technology), anti–CAMKII P-T286/T287 (Cell Signaling Technology), anti–total Phospholamban (Thermo Fisher Scientific), anti–Phospholamban P-S16 (Santa Cruz Biotechnology, Inc.), anti–Phospholamban P-T17 (Badrilla), and anti–total and P-Ser 23/24 Troponin I (Cell Signaling Technology). After incubation with the appropriate HRP-conjugated secondary antibody, membranes were incubated with ECL substrate for detection of HRP enzyme activity (Thermo Fisher Scientific) and visualized in a Syngene gel documentation system. Images were splined (Arganda-Carreras et al., 2006) as needed and quantified by ImageJ analysis (National Institutes of Health). Student’s t test was used for statistical significance assessment.

**RT-PCR**

Total RNA was extracted from isolated cardiomyocytes, heart, or cultured cells using the RNeasy Mini kit (QIAGEN). Following the manufacturer’s procedure, cDNA was reverse-transcribed using the SuperScript III First-Strand Synthesis System (Life Technologies). Real-time PCR was performed with iTaq Universal SYBR-green Supermix (Bio-Rad Laboratories) in a MX3000P (Agilent Technologies) apparatus with the following program: 95°C for 3 min; 95°C for 10 s, 60°C for 20 s for 40 cycles; 95°C for 1 min, and down to 55°C (gradient of 1°C) for 41 cycles (melting curve step). Values were expressed in Δ Ct using GAPDH as a reference.

Primers were as follows: TrkB common forward, 5′-AGCAATCTGGGAGCATCCT-3′; TrkB.FL reverse, 5′-CTGGCAGAGTCATC-GTCTG-3′; TrkB.T1 reverse, 5′-TACCCATCGATGGATCTT-3′; GAPDH forward, 5′-TGGCAGCTACACGACAATC-3′; GAPDH reverse, 5′-ATGAGGCCCAGGTCGCCAC-3′; BDNF forward, 5′-GCAGCTACGGCAGCTGACATC-3′; BDNF reverse, 5′-CAAGG-CACCGTGACTCGTA-3′; NT3 forward, 5′-CCCCGCACGGCGA-TAATG-3′; NT3 reverse, 5′-CGCTGGGACGTCTGATGA-3′; NT4 forward, 5′-TACCTCTAAAGGGGGGCCC-3′; NT4 reverse, 5′-CTTGGGAGGAGGAGGAGG-3′. RT-PCR products were separated in a 2% agarose gel stained with ethium bromide.

**Langendorff heart preparation**

Male mice (2 mo, 19–25 g) were injected with heparin (5,000 U/kg i.p.) and after 10 min were anesthetized with Avertin (150 mg/kg i.p.). Hearts were quickly removed from the chest and put into 16–18°C calcium-free modified Krebs solution containing 118 mmol NaCl, 23 mmol NaHCO3, 3.2 mmol KCl, 1.2 mmol KH2PO4, 1.2 mmol MgSO4, 11 mmol glucose, and 2 mmol sodium pyruvate before being mounted in a Langendorff perfusion system (Broadley, 1979). Hearts were perfused with modified Krebs solution containing 1.5 mM CaCl2 (37.5°C) via the aorta. All solutions were bubbled with 95% O2–5% CO2, pH 7.40, and kept at 37°C. An inflatable water-filled balloon was inserted into the left ventricle via a small incision in the left atrium for measurement of the left ventricle pressure (BIOPAC Systems Inc.). Perfusion pressure and coronary flow were also continuously monitored via a differential pressure transducer. All channels were fed to a digitada 1322a (Axon) for digitalization storage and analysis using Igor 4.0 (Wave-Metrics) or Clampfit (Axon) software.

After mounting, the hearts were equilibrated for 10 min at a perfusion pressure of 80 mmHg and at an end-diastolic pressure of 5–10 mmHg. Only hearts with a sinus heart rate ≥300 bpm and a left ventricle systolic pressure ≥70 mmHg at the end of the equilibration period were included in the studies. After the equilibration period, hearts were paced by platinum electrode at 420 bpm and the baseline contractile parameters and coronary flow were recorded for an additional 10 min. Neutrophils were added to the Krebs solution immediately before use from frozen stocks and injected into the flow stream in a T tube placed before the temperature control unit. Caffeine (5 mM in Krebs) and denatured BDNF (10 ng in Krebs; 95°C for 5 min) were used, respectively, as positive and negative control. The total volume from the injection point to the tip of the cannula was 1.4 ml and drugs were always injected in a 50-µl volume. The effect of any substance on heart parameters was calculated as a percentage of the mean value from 20 s before the injection. 1-NMPP1 was purchased from EMD Millipore and NT3 and NGF were purchased from Alomone Laboratories.

**Adult mouse cardiomyocyte isolation**

2-mo-old male mice were injected with heparin (5,000 U/kg i.p.) and after 10 min were anesthetized with Avertin (150 mg/kg i.p.). Hearts were quickly removed from the chest cavity and put into ice-cold calcium-free solution in ultrapure H2O (specific resistance >21 MOhm) containing 133.5 mM NaCl, 4 mM KCl, 1.2 mM NaH2PO4, 1.2 mM MgSO4, 10 mM N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid, and 11 mM glucose, adjusted to pH 7.4 with NaOH. The heart, cannulated through the aorta with a round tip 21G needle was mounted in a Langendorff perfusion system and perfused at a pressure of 80 mmHg for 5 min with Ca2+-free solution containing 1 mg/ml BSA (Sigma-Aldrich) and subsequently for 8–15 min with the same solution containing 25 mM Ca2+ together with collagenase type II (200–350 U/mg; Worthington.
Biochemical Corporation). Collagenase perfusion was determined by the coronary flow variation and stopped when it increased consistently. Ventricles were then cut into small pieces and gently triturated for 1–3 min with a fire-polished Pasteur pipette. The resulting cell suspension was then passed through a 250-mesh filter and centrifuged at 150 rpm for 5 min. After resuspension in fresh control solution with 100 mM Ca\(^{2+}\), cells were washed again and resuspended in control solution containing 200 mM Ca\(^{2+}\) at 22–23°C (Wolska and Solaro, 1996).

**Measurement of intracellular Ca\(^{2+}\) transients**

Calcium tolerant adult cardiomyocytes were loaded with Indo1-AM for 1 h, washed with control solution, and left at room temperature for at least 45 min to allow deesterification of the dye. Loading solution was prepared from a control solution containing 0.2 mM Ca\(^{2+}\) and 1 mM Indo1-AM (1 mM stock in dimethyl sulfoxide; Life Technologies) dissolved first in Pluronic surfactant (PowerLoad 100x; Life Technology) with 1 mg/ml BSA. Cardiomyocytes were field stimulated (0.5/s) with platinum electrodes (FHC Inc.) and recordings were made at 27°C in 1 mM Ca\(^{2+}\) solution. BDNF was applied at 50 ng/ml using a pipocospritzer at 30 hPa and a glass pipette with 1-M Ohm tip resistance. Excited at 340 nM, indo1-AM emission was split into two channels and passed through 405/10-nm (calcium-bound emission) and 488/10-nm (calcium-free emission) fluorescence filters. Light collected by photodiodes (Till Photonics) was digitally converted at 10 KHz (pClamp 10 and Digidata 1322a) and computed and the information was stored.

**Calcium current recordings**

Ca\(^{2+}\)-tolerant cardiomyocytes cells were placed in a recording chamber and perfused with a Na\(^{+}\)-free solution containing 137 mM tetraethylammonium chloride, 1 mM MgCl\(_2\), 2 mM CaCl\(_2\), 10 mM Hepes, and 10 mM glucose (pH 7.4 with TEA-OH) at a flux of 1 ml/min at 27°C. The pipette solution contained 111 mM CsCl, 20 mM tetraethylammonium chloride, 10 mM glucose, 14 mM EGTA, 10 mM Hepes, and 5 mM MgATP (pH 7.3 with CsOH). Pulled borosilicate glass pipettes at ~3–4 MOhm filled with pipette solution were used to obtain gigaseal on cardiomyocytes and subsequent whole-cell voltage clamp. Currents (I\(_{Ca-L}\)) were elicited by applying depolarizing voltage steps from a holding potential of ~−60 mV (~−50 mV to +70 mV, 10-mV increments) and recorded (filtered at 2 kHz through a 4-pole low-pass Bessel filter and digitized at 5 kHz) with a Multiclamp 700B (Axon) using pClamp software (Axon). The maximum absolute value of the current obtained (in pA) was divided by the cell capacitance (in pF).

**Heart histology**

Hearts from anesthetized mice were quickly removed from the chest cavity, placed in ice-cold calcium- and magnesium-free PBS, cannulated through the aorta with a 21G needle, and perfused at a constant flow of 1 ml/min for 2 min with calcium- and magnesium-free PBS containing 20 mM KCl to induce cardiac relaxation. After that, the heart was perfused with 4% PFA in PBS for 10 min, cut in half horizontally, and fixed overnight at 4°C before paraffin embedding, sectioning at 7 μm, and staining with hematoxylin and eosin or Masson trichromic.

**Mouse embryonic cardiomyocytes**

Mouse embryonic cardiomyocytes were prepared as previously described (Graciotti et al., 2011). In brief, embryonic 17.5-d hearts were dissected, washed with ice-cold DMEM, minced, and incubated in 0.25% trypsin (Gibco) at 37°C for 13 min. After centrifugation (1,000 rpm for 5 min), the pellet was resuspended and incubated again in 0.25% trypsin at 37°C for 13 min, centrifuged, resuspended, and incubated in DMEM with 0.2% collagenase (collagenase type II) at 37°C for 30 min. Cells were then plated in a 10-cm dish in DMEM with 10% FBS media. After 1 h, the floating cells were collected and plated in DMEM/10% FBS media at a density of 160,000 cells/cm\(^2\) in 6-well plates pretreated with 40 μg/ml laminin for 1 h. Embryonic cardiomyocytes were cultured for at least 7 d to allow differentiation before adding fresh media for a conditioning period of 48 h. Supernatants were applied fresh (without freezing/thawing) to C2C12 cells stably expressing TrkB.Kin. Recombinant BDNF (Alamone Laboratories) and a recombinant TrkB Fe Chimera (R&D Systems) were used as controls.

**Echocardiography**

Echocardiography was performed on 6-mo-old mice using a VisualSonic Vevo 770 equipped with a 30-MHz probe as previously reported (Gao et al., 2011).

**β-Galactosidase staining**

For β-galactosidase staining, adult hearts retro-perfused with 4% PFA were embedded in OCT mounting medium before freezing and sectioning at 20 μm. Sections were washed three times for 5 min with 100 mM sodium phosphate buffer, 20 mM MgCl\(_2\), 0.01% sodium deoxycholate, and 0.02% NP-40, and then stained for 2 h at 30°C with PBS without Mg\(^{2+}/Ca^{2+}\), 5 mM K\(_4\)Fe(CN)\(_6\), 5 mM K\(_3\)Fe(CN)\(_6\), 2 mM MgCl\(_2\), and 1 mg/ml X-gal, rinsed in dH\(_2\)O, and counterstained with neutral red for 40 s. After three rinses in 100% ethanol, coverslips were mounted in xylene.

**Online supplemental material**

Fig. S1 shows that BDNF does not alter the spontaneous cardiac beating frequency. Fig. S2 shows that BDNF increases systolic and decreases diastolic pressure but has no effect on coronary flow. Fig. S3 provides evidence that the TrkB.F616A mouse model is not suitable for this type of analysis because 1-NMPP1 exerts a potent inotropic and lusitropic effect in Langendorff-perfused hearts that occludes BDNF effect on contractility. Fig. S4 shows that TrkB.T1 deletion does not cause obvious early postnatal cardiac developmental defects. Fig. S5 demonstrates that BDNF is the main neurotrophin expressed in neonatal and adult cardiomyocytes although NT3 but not NGF causes an increase in contractility of WT but not TrkB.T1-deficient hearts. Table S1 provides the functional parameters recorded in Langendorff-perfused hearts from WT and T1\(^{−/−}\) animals. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.201502100/DC1. Additional data are available in the JCB DataView at http://dx.doi.org/10.1083/jcb.201502100.dv.

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