Functional Characteristics of ES Cell–derived Cardiac Precursor Cells Identified by Tissue-specific Expression of the Green Fluorescent Protein

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Abstract. In contrast to terminally differentiated cardiomyocytes, relatively little is known about the characteristics of mammalian cardiac cells before the initiation of spontaneous contractions (precursor cells). Functional studies on these cells have so far been impossible because murine embryos of the corresponding stage are very small, and cardiac precursor cells cannot be identified because of the lack of cross striation and spontaneous contractions.

In the present study, we have used the murine embryonic stem (ES, D3 cell line) cell system for the in vitro differentiation of cardiomyocytes. To identify the cardiac precursor cells, we have generated stably transfected ES cells with a vector containing the gene of the green fluorescent protein (GFP) under control of the cardiac α-actin promoter. First, fluorescent areas in ES cell–derived cell aggregates (embryoid bodies [EBs]) were detected 2 d before the initiation of contractions. Since Ca\(^{2+}\) homeostasis plays a key role in cardiac function, we investigated how Ca\(^{2+}\) channels and Ca\(^{2+}\) release sites were built up in these GFP-labeled cardiac precursor cells and early stage cardiomyocytes. Patch clamp and Ca\(^{2+}\) imaging experiments proved the functional expression of the L-type Ca\(^{2+}\) current (I\(_{\text{Ca,L}}\)) starting from day 7 of EB development. On day 7, using 10 mM Ca\(^{2+}\) as charge carrier, I\(_{\text{Ca,L}}\) was expressed at very low densities 4 pA/pF. The biophysical and pharmacological properties of I\(_{\text{Ca,L}}\) proved similar to terminally differentiated cardiomyocytes. In cardiac precursor cells, I\(_{\text{Ca,L}}\) was found to be already under control of cAMP-dependent phosphorylation since intracellular infusion of the catalytic subunit of protein kinase A resulted in a 1.7-fold stimulation. The adenylyl cyclase activator forskolin was without effect. IP\(_3\)-sensitive intracellular Ca\(^{2+}\) stores and Ca\(^{2+}\)-ATPases are present during all stages of differentiation in both GFP-positive and GFP-negative cells. Functional ryanodine-sensitive Ca\(^{2+}\) stores, detected by caffeine-induced Ca\(^{2+}\) release, appeared in most GFP-positive cells 1–2 d after I\(_{\text{Ca,L}}\). Co-expression of both I\(_{\text{Ca,L}}\) and ryanodine-sensitive Ca\(^{2+}\) stores at day 10 of development coincided with the beginning of spontaneous contractions in most EBs.

Thus, the functional expression of voltage-dependent L-type Ca\(^{2+}\) channel (VDCC) is a hallmark of early cardiomyogenesis, whereas IP\(_3\) receptors and sarcoplasmic Ca\(^{2+}\)-ATPases are expressed before the initiation of cardiomyogenesis. Interestingly, the functional expression of ryanodine receptors/sensitive stores is delayed as compared with VDCC.

Key words: GFP • cardiac α-actin promoter • in vitro cardiomyogenesis • ion channels • Ca\(^{2+}\).

The heart is the first organ to be formed during murine embryonic development. Between E7.5 and E8, the generation of a single heart tube is initiated, and from E8.5 to E9 the first contractions of this primitive structure are observed (Fishman and Chien, 1997). While the heart undergoes further changes during later stages of development, essential components responsible for the initiation of regular contractile activity are already established at this early stage. Indeed, the first transcripts of sarcomeric contractile proteins are already detectable on E7.5 (Sassoon et al., 1988; Sanchez et al., 1991). There is only sparse knowledge of the sequential expression of ion channels and Ca\(^{2+}\) release stores, both playing a fundamental role in cardiac function at these initial stages of development. For terminally differentiated cardiomyocytes, it is well established that voltage-dependent L-type Ca\(^{2+}\)
channels (VDCC) are responsible for transmembrane Ca\(^{2+}\) influx which secondarily leads to Ca\(^{2+}\) induced Ca\(^{2+}\) release (CICR) (Fabiato, 1985; du Bell and Houser, 1987; Barcenas-Ruiz and Wier, 1987; Nabauer et al., 1989) from the sarcoplasmatic reticulum (SR) through ryanodine sensitive Ca\(^{2+}\) stores (Meissner, 1994). The calcium-induced calcium release (CICR)-mediated increase of the free cytosolic Ca\(^{2+}\) concentration ([Ca\(^{2+}\)\(_i\)]) is a prerequisite for cardiac contraction. Increased [Ca\(^{2+}\)], is lowered by reuptake via the thapsigargin (Tg)-sensitive sarcoplasmic Ca\(^{2+}\)-ATPase and extrusion via the Na\(^{+}\)-Ca\(^{2+}\) exchanger as well as the sarcosomal Ca\(^{2+}\)-ATPase (Bers, 1997). Even though changes in the regulation of VDCC during cardiac development have been reported for E11–13 murine cardiomyocytes (Davies et al., 1996), as well as for the perinatal stage (Tohse et al., 1992a,b; Masuda et al., 1995) and ES cell–derived cardiomyocytes (Maltsev et al., 1994), when and how cardiomyocytes differentiating from the mesodermal lineage establish intracellular Ca\(^{2+}\) stores and the regulation of VDCC remains obscure. The latter mechanism plays a key role in the adult heart for the control by the autonomic nervous system (Osterrieder et al., 1982; Reuter, 1983; Hartzell and Fischmeister, 1986; Trautwein and Hescheler, 1990).

The aim of the present study was to investigate the expression and regulation of VDCC as well as of the establishment of Ca\(^{2+}\) release channels in single cardiomyocytes before the initiation of spontaneous contractions (cardiac precursor cells). Studies on these early stage cells from murine embryos have not been performed so far because the heart is very small at this stage, and isolation procedures have proved impossible before stage E11 (An et al., 1996; Davies et al., 1996).

In the past, we have used embryonic stem (ES) cells for the in vitro differentiation and isolation of cardiomyocytes to circumvent this problem (Wobus et al., 1991; Maltsev et al., 1994). However, at the very early stages of development, cardiomyocytes cannot be recognized even in vitro because of the lack of cross striation and beating (Davies et al., 1996; Hescheler et al., 1997). To identify these cardiac precursor cells, we have established ES cell clones stably transfected with the gene of the jellyfish Aequorea victoria green fluorescent protein (GFP) (Prasher et al., 1992; Chalfie et al., 1994) under control of a cardiac-specific promoter. Since transcripts of α-actin are among the earliest detectable in the developing heart (Sassoon et al., 1988; Lyons et al., 1991), and its expression was shown to be cardiac specific in the ES cell system before the initiation of spontaneous contractions (Metzger et al., 1996), we have chosen the cardiac α-actin promoter to drive the GFP expression. Based on a well-established protocol (Doetschman et al., 1985; Wobus et al., 1991; Metzger et al., 1995), ES cells were differentiated into cell aggregates (embryoid bodies [EBs]) containing cardiomyocytes. The first spontaneously beating areas are noticed in 9-d-old EBs. In 15–18-d-old EBs, terminally differentiated cardiomyocytes are detected with almost identical morphological and electrophysiological features as murine perinatal cardiomyocytes (Hescheler et al., 1997).

Taking advantage of the tissue-specific GFP expression in ES cell–derived cardiomyocytes, we here describe the functional characterization of cardiac precursor cells with patch clamp and Ca\(^{2+}\) imaging techniques. We demonstrate that VDCC are already expressed at very low density in 7-d-old cardiac precursor cells and stimulated via cAMP-dependent protein kinase A (PKA)-dependent phosphorylation. However, the functional expression of ryanodine-sensitive Ca\(^{2+}\) receptors/stores was delayed in most cells compared with VDCC, and their coexpression coincided with the onset of spontaneous contractions.

Materials and Methods

Vectors

The pCX-EGFP expression vector containing the enhanced version of the GFP coding sequence EGFP (CLONTECH Laboratories, Palo Alto, CA) under the chicken β-actin promoter (Ikawa et al., 1995; Okabe et al., 1997) was provided by Dr. Okabe (University of Osaka, Japan) and modified as follows: The vector pPv/B-Act-lacZ containing the (~440 to +6) segment of the human cardiac α-actin promoter (Minty and Kedes, 1986; Pari et al., 1991) was provided by Dr. M.W. McBurney (University of Ottawa, Canada). The promoter was excised from pPv/B-Act-lacZ by SalI and HindIII restriction enzymes. The pCX-EGFP was digested with SnaBI and ApaI restriction enzymes to excise the chicken β-actin promoter, which was replaced by the above mentioned SalI-HindIII fragment of the cardiac α-actin promoter by blunt-end ligation. Then, Sall-Xbal restriction fragment containing the Neomycin (G418) resistance gene from pTL2 NeoR (provided by Dr. Tarakhovsky, Institute for Genetics, Cologne, Germany) was inserted by blunt-end ligation in the Sall site of pCX-EGFP. The resulting vector pCX-(α-act)-EGFP-NeoR was used for electroporation of ES cells of the line D3. ES cells were cultured on fibroblast feeder layers in DME supplemented with 15% FCS (GIBCO BRL; Life Technologies, Gaithersburg, MD), 1× nonessential amino acids (GIBCO BRL) and 0.1 mM β-mercaptoethanol (Sigma Chemical Co., St. Louis, MO).

Electroporation and Selection Procedure

pCX-(α-act)-EGFP-NeoR was linearized by AatII restriction to linearize the vector and destroy the CMV-enhancer. Electroporation and G418 selection was performed according to standard protocols. The pCX-(α-act)-EGFP-NeoR-transfected ES clones with GFP fluorescence comparable to wild-type ES cells were selected using FACS® and used for the differentiation protocol. EBs were generated using standard protocols as previously described (Wobus et al., 1991). In brief, hanging drops were established by plating a suspension of ES cells in final concentration of 0.020–0.025 × 10⁶ cells/ml in 20 µl (400–500 cells) of DME + 20% FCS on the lids of 24-well plates. During all stages of development, growing EBs were washed out with 10 ml DME + 20% FCS into bacterial dishes and incubated for an additional 4 d. Then, EBs were plated separately on gelatin-pretreated 24-well plates. During all stages of development, growing EBs were monitored under the fluorescent microscope using an FITC filter set (Zeiss, Jena, Germany).

Since the investigated clones were selected using G418, their characteristics may differ from wild-type ES cells. For this reason, several clones (A1, A10, A12, and A17) were tested. No difference between selected clones and parental cell line in regard to differentiation and initiation of spontaneous contractions was noticed.

FACS®

For FACScan® analysis, 10–20 EBs of different stages of development were washed with PBS and then dissociated to a single cell suspension by trypsin treatment for 2–3 min (120 µl of trypsin/EDTA solution). Then, 1 ml of DME + 20% FCS was added to the single-cell suspension. After centrifugation (1,000 rpm) for 5 min, the cells were resuspended in 0.5–1.0 ml of PBS containing Ca\(^{2+}\) (1 mM) and Mg\(^{2+}\) (0.5 mM).

1. Abbreviations used in this paper: ANP, atrial natriuretic peptide; CICR, calcium-induced calcium release; DAB, 3,3-diamobenzidine-tetrahydrochloride; EB, embryoid body; ES, embryonic stem; GFP, green fluorescent protein; PKA, cAMP-dependent protein kinase A; SR, sarcoplasmic reticulum; Tg, thapsigargin; VDCC, voltage-dependent L-type Ca\(^{2+}\) channels.
The GFP expression by ES cell-derived cells of different age was analyzed on a FACSCalibur™ flow cytometer (Becton Dickinson) equipped with a 488-nm argon-ion laser (15 mW). Cells were resuspended to a concentration of 5 × 10⁶ cells/ml in PBS (pH 7.0, 0.1% BSA) and then analyzed on the FACSCalibur™ with a minimum of 10,000 viable cells acquired for each sample. The emitted fluorescence of GFP was measured at 530 nm (FTTC band pass filter). Live gating was done by addition of propidium iodide (2 μg/ml) to the samples immediately before measurement. Cells with a negative propidium iodide staining (585-nm band pass filter) showed higher side scattering signals compared with the viable PI-negative cells. Nonviable cells were excluded from the subsequent analysis by gating on cells with low SSC signals. Nontransfected ES cells of the cell line D3 were used for negative controls. Analyses were performed using CellQuest™ software (Becton Dickinson).

**Dissociation of EBs and Preparation of Single Cardiomyocytes**

For the experiments using single cells, whole EBs, or for the later stages, beating areas of 20–30 EBs were dissected and isolated by enzymatic dispersion, using collagenase B (Boehringer, Ingelheim, Germany), as described in more detail by Maltev et al. (1994). The solution used for the dissociation of the dissected areas was the following (in mmol/L): 120 NaCl, 5.4 KCl, 5 MgSO₄, 0.03 CaCl₂, 5 Na pyruvate, 20 glucose, 20 taurine, 10 Hepes, and 0.5–1 mg/ml collagenase B. pH 6.9 (NaOH). The dissociated material was plated onto gelatin-coated glass coverslips and put into the incubator at 20% FCS containing DMEM.

**Immunocytochemistry**

Single, enzymatically dissociated ES cell-derived cells (11–14 d) were plated on gelatin-covered glass coverslips overnight. Cells were subsequently fixed in a solution containing 4% paraformaldehyde in 0.1 M PBS buffer, pH 7.4, for 15 min. After fixation, single-cell preparations were washed several times in 0.1 M PBS and further treated with 0.1% Triton X-100 (Sigma, Deisenhofen, Germany) connected to the TV port of the microscope. Fluorescence images (50–100-ms exposure time) were acquired at a rate of 0.33 Hz using an intensified charge coupled device camera (Thetha, München, Germany) connected to the TV port of the microscope. Fluorescence imaging experiments were performed at room temperature. Single-cell preparations were observed through filter set 15 (Zeiss; excitation BP 45–490, emission BP 515–565), which allows recognition of GFP fluorescence, and filter set 10 (Zeiss; excitation BP 340, 380, and 488 nm) to the samples immediately before measure-ment. Cells with a positive propidium iodide staining (585-nm band pass filter) showed higher side scattering signals compared with the viable PI-negative cells. Nonviable cells were excluded from the subsequent analysis by gating on cells with low SSC signals. Nontransfected ES cells of the cell line D3 were used for negative controls. Analyses were performed using CellQuest™ software (Becton Dickinson).

**Patch Clamp Recordings of I_{Ca}**

Standard whole-cell recording techniques (Hamill et al., 1981) were used (model Axopatch 200A amplifier; Axon Instruments, Foster City, CA). Data were acquired using the Iso2 software package (MFK, Niedernhausen, Germany), sampled at 2 kHz and stored on hard disk. All patch clamp experiments were performed at room temperature. Pipettes were made on a DMZ Universal Puller (München, Germany) from 1.5-mm borosilicate glass capillaries (Clark Electromedical Instruments, Reading, UK). The compositions of the different recording solutions used were (in mM) extracellular solution: 135 NaCl, 5 KCl, 2 MgCl₂, 5 Hepes, 10 glucose, pH 7.4 (NaOH). For the high K+ solution, the composition was 135 KCl, 5 NaCl, 2 MgCl₂, 2 CaCl₂, 5 Hepes, pH 7.4 (KOH).

**Results**

**Establishment and Specificity of the Cardiac α-Actin Promoter–driven GFP Expression and Identification of Cardiac Precursor Cells**

First, we investigated whether GFP could be stably ex-
pressed in ES cells under control of the α-actin promoter and what pattern of GFP expression could be observed during differentiation. The pCX-(α-act)-EGFP-Neo<sup>B</sup>-transfected ES cells as well as EBs before plating (Fig. 1, A and B) displayed only weak fluorescence under microscopic observation. However, at the 7-d stage, i.e., 1 d after plating, areas with distinct fluorescence could be detected (data not shown). Most of these GFP-positive areas developed 48–72 h later into spontaneously contracting regions (Fig 1, C and D). During all stages of cardiomyogenesis, strong fluorescence was exclusively detected in these beating areas (Fig. 1, C and D). This overlap between GFP expression and beating clearly indicated the cardiac specificity of the human cardiac α-actin promoter.

The microscopic pattern of GFP expression was quantitatively assessed using FACS<sup>®</sup>. The profile of pCX-(α-act)-EGFP-Neo<sup>B</sup>-transfected ES cells confirmed low fluorescence intensities at the ES cell stage (Fig. 2 B) comparable to nontransfected wild-type ES cells (Fig. 2 A). During EB development, an enlargement of the initial peak to higher fluorescence intensities was observed. In some clones, particularly with low initial fluorescence (Fig. 2 B, 0d), the appearance of a second peak corresponding to GFP-expressing cells was noticed (Fig. 2 B, 7d and 12d). In 7-d-old EBs, the fraction of GFP-positive cells amounted to 30–50% of the whole EB. The FACS<sup>®</sup> profile of EBs containing clusters of spontaneously contracting cardiomyocytes showed a further broadening of the fluorescent peak to higher fluorescence intensities (Fig. 2 B, 12d), possibly corresponding to the contracting cardiomyocytes. This was corroborated by measuring GFP fluorescence intensities of single cells isolated from EBs at different stages of development. Very low fluorescence levels were detected in 0–4-d-old cells, but a clear increase and diversification of the GFP fluorescence intensity was observed in cells from 8 d and more prominently from 10-d-old EBs. The highest fluorescence intensities were detected in spontaneously beating cardiomyocytes (data not shown).

The specificity of the GFP expression in pCX-(α-act)-EGFP-Neo<sup>B</sup>-transfected ES cells was further corroborated by immunocytochemistry on single ES cell–derived cells. GFP expression under the α-cardiac actin promoter proved to be tightly correlated with α-actin antibody staining (Fig. 3, A and B). Almost all (95%) of the GFP-positive cells (11 and 14 d) showed α-actin containing (n = 343). Furthermore, the GFP-positive cells displayed morphological features typical for cardiomyocytes. Early stage cardiomyocytes were small and round and showed a homogeneous distribution of myofilament specific proteins (Fig. 3, A and B) (Hescheler et al., 1997). Late-stage cardiomyocytes were elongated with a typical pattern of condensed α-actinin, indicating the development of sarcomeres. In the late-stage cells, 93% of the GFP-expressing cells were α-actinin positive (Fig. 3, C and D; n = 96, 11–14 d).

Since 7-d-old GFP-positive cells had low α-actin content and did not yet display morphological features typical for cardiomyocytes, the more sensitive DAB method for immunostaining was used. 32% of 7-d-old cells were DAB positive (n = 191), whereas only 3.7% of DAB-positive cells (n = 161) were detected in undifferentiated D3 cells. This percentage of α-actin–containing cells corresponded well with the fraction of GFP-positive cells revealed with FACS<sup>®</sup> in 7-d-old EBs. To confirm further that GFP-positive cells (7–9 d) were indeed cardiac precursor cells staining with ANP, known to be expressed at early stages of cardiomyogenesis but not skeletal myogenesis (Miller-Hance et al., 1993; Hescheler et al., 1997), was performed. All GFP-positive cells were ANP positive (data not shown), unequivocally proving their cardiac nature.

**VDCC Are Expressed in α-Actin Promoter–Driven**

**GFP-positive Cardiac Precursor Cells and Upregulated by Protein Kinase A**

Initially, electrophysiological experiments were performed on several GFP-positive clones (A1, A10, and A17), and...
Fluorescence intensity

Figure 2. FACS® profiles of ES cells and EB-derived cells expressing GFP under control of the human cardiac α-actin promoter (pCX-(α-act)-EGFP-NeoR). FACS® analysis was performed on different stages of EB development as indicated in the upper left corners. The M1 bar marks the range of GFP fluorescence. GFP fluorescence intensities of nontransfected ES cells (wt, A) and pCX-(α-act)-EGFP-NeoR-transfected ES cells (B) were similar and characterized by low fluorescence intensities. ES cells carrying the cardiac pCX-(α-act)-EGFP-NeoR develop a fluorescent peak of high intensity during differentiation of EBs (7d and 12d). After appearance of spontaneously contracting cardiomyocytes, a further enlargement to higher fluorescence intensities was observed (12d).

no difference in their characteristics between the parental ES cell line D3 and the different clones were noticed. For the functional investigation of GFP-positive cells presented in this study, cell clones (A1 and A17) were chosen in which the fluorescence of ES cells was comparable to wild-type ES cells but at later stages developed a second fluorescent peak observed with FACS®. These clones allowed the easy detection of GFP-positive cells already at the cardiac precursor stage. All EBs used for the isolation of single cells before 9 d of differentiation did not contain contracting areas.

First, we investigated at which time point I\textsubscript{Ca} becomes functionally active during very early cardiac development. Single-cell Ca\textsuperscript{2+} imaging was performed, using the cell membrane-permeant Ca\textsuperscript{2+} indicator fura-2AM. From all cells within the visual field GFP fluorescence was determined, thereafter [Ca\textsuperscript{2+}]\textsubscript{i} was monitored. GFP-positive and -negative cells were characterized by stable resting [Ca\textsuperscript{2+}]\textsubscript{i} of 92.7 ± 10.5 nM (n = 10) and of 91.7 ± 9.8 nM (n = 10), respectively. As shown in Fig. 4 A, application of the dihydropyridine BayK8644 (0.5 μM), a selective opener of VDCC, led to a [Ca\textsuperscript{2+}]\textsubscript{i} increase in a GFP-positive cell associated with [Ca\textsuperscript{2+}]\textsubscript{i} oscillations (n = 2). Combined superfusion of BayK8644 and high K\textsuperscript{+} (140 mM) solution evoked a sustained increase of [Ca\textsuperscript{2+}]\textsubscript{i}. Nisoldipine (0.5 μM), a selective blocker of VDCC, led to a decline of [Ca\textsuperscript{2+}]\textsubscript{i}, close to baseline levels (Fig. 4 A, n = 8), indicating the exclusive involvement of I\textsubscript{Ca}. The [Ca\textsuperscript{2+}]\textsubscript{i} increase evoked by coapplication of BayK8644 and high K\textsuperscript{+} solution was 252 ± 37 nM (n = 6) in 8-d-old cells. There was no change of [Ca\textsuperscript{2+}]\textsubscript{i} in cells with no or only weak GFP fluorescence (Fig. 4 B, n = 20).

In 187 cells, the correlation between GFP fluorescence intensities and the functional expression of VDCC was investigated. As demonstrated in Fig. 4 C, a rise of [Ca\textsuperscript{2+}]\textsubscript{i} upon superfusion with BayK8644/high K\textsuperscript{+} was observed as early as 7 d, and at that time only in one cell. This cell did not display a difference in the GFP fluorescence intensity compared with nonresponding cells (Fig. 4 C). In the later stages (8–11 d), there was a clear correlation between GFP intensity and the expression of VDCC, seen by a rise of [Ca\textsuperscript{2+}]\textsubscript{i} (Fig. 4 C, n = 5). Combined superfusion with BayK8644/high K\textsuperscript{+} solution on 9–11 d, almost all cells with bright GFP fluorescence responded to BayK8644/high K\textsuperscript{+} with a large increase of [Ca\textsuperscript{2+}]\textsubscript{i} (1052.9 ± 223.8 nM, n = 20). Thus, at this stage of development the GFP expression was strongly correlated with I\textsubscript{Ca} expression.

The experiments using Ca\textsuperscript{2+} imaging demonstrated that I\textsubscript{Ca} was already functionally expressed during the initial steps of cardiomyogenesis. To investigate in more detail the biophysical profile, current density, and the regulation of I\textsubscript{Ca} in cardiac precursor cells, we performed whole-cell patch clamp experiments on GFP-positive cells. These were identified using a fluorescence microscope. In control experiments, we found that I\textsubscript{Ca} was, besides small amplitude K\textsuperscript{+} currents, the prominent ion channel detected at this early stage of development. Since initial experiments showed, that I\textsubscript{Ca} was expressed at very low densities, 10 mM Ca\textsuperscript{2+} as charge carrier was used. I\textsubscript{Ca} was evoked applying depolarizing voltage steps from a holding potential of −80 mV to a test potential of +10 mV. The earliest time point at which I\textsubscript{Ca} could be detected was 7 d. As can be seen in Fig. 5 A, the current–voltage relationship of I\textsubscript{Ca} in a 7-d-old cardiac precursor cell proved to be similar to that of an 9-d-old cardiomyocyte (Fig. 5 B). The threshold of activation was close to −40 mV, and peak I\textsubscript{Ca} was measured at +10 mV (Fig. 5 A and B). I\textsubscript{Ca} was detected in 22.2% of the GFP-positive 7-d-old cells, but at very low density
The percentage of GFP-positive cells expressing ICa increased dramatically within the next 24 h and was close to 80% at 10 d (Fig. 5 D). GFP-negative cells did not express VDCC in 7–10-d-old EBs (n = 20; Fig. 5 C). The current was identified as cardiac ICa on the basis of its fast activation kinetics, current–voltage relationship (Fig. 5), and sensitivity to nisoldipine (2 μM, n = 2) (Fig. 6 A). To show the blocking effect of ni-

Figure 3. Immunocytochemical pattern of α-actin and α-actinin staining in single ES cell–derived cells expressing GFP under control of the human cardiac α-actin promoter. (A and B) Immunostaining with α-actin antibody of a GFP-positive cell. This cell displayed characteristic morphological features for an early stage cardiomyocyte with the typical round shape morphology and the low cytoplasm/nucleus ratio. (A) The GFP-derived fluorescence was spread over the whole cell. (B) The α-actin immunofluorescence was primarily expressed in the perinuclear region. (C and D) Comparison of GFP expression under control of the human cardiac α-actin promoter and α-actinin immunoreaction of a more elongated, late-stage cardiomyocyte. (C) In this more differentiated cardiomyocyte, the GFP fluorescence was spread over the entire cell. (D) The α-actinin immunofluorescence displayed a typical cross pattern, indicating sarcomeric organization in this cardiomyocyte. Bar, 10 μm.

(3.8 ± 1.3 pA/pF, n = 54) (Fig. 5, C–E). The percentage of GFP-positive cells expressing ICa increased dramatically within the next 24 h and was close to 80% at 10 d (Fig. 5 D). GFP-negative cells did not express VDCC in 7–10-d-old EBs (n = 20; Fig. 5 C). The current was identified as cardiac ICa on the basis of its fast activation kinetics, current–voltage relationship (Fig. 5), and sensitivity to nisoldipine (2 μM, n = 2) (Fig. 6 A). To show the blocking effect of ni-

Figure 4. Functional expression of VDCC determined with Ca2+ imaging in single GFP-positive cells of different stages. Single ES cell–derived cells were loaded with the membrane-permeant form of the Ca2+ indicator fura-2. First, individual cells were tested for their GFP fluorescence using 488-nm excitation light (1 s) and an FITC filter block. Then, the cytosolic Ca2+ concentration [Ca2+]i was monitored using a fura-2 filter block and 340/380 excitation light. The recording chamber was subsequently perfused with BayK8644/high K+–containing solution to depolarize the membrane potential and test for the functional expression of VDCC. (A) A GFP-positive cell, with an oscillatory [Ca2+]i increase upon application of the selective VDCC agonist BayK8644 (0.5 μM). Subsequent perfusion of BayK8644 and high K+ (140 mM) leads to a sustained increase in [Ca2+]i, which was blocked by the selective VDCC antagonist nisoldipine (0.5 μM). (B) In a GFP-negative cell, application of BayK8644/high K+ did not induce changes of [Ca2+]i. (C) GFP fluorescence intensities and the functional expression of VDCC proved strongly correlated. Cells derived from 6-d-old EBs had low GFP fluorescence and no changes in [Ca2+]i upon BayK8644/high K+ perfusion. On 7 d, only one cell displayed a [Ca2+]i increase upon BayK8644/high K+ perfusion, but no difference in GFP fluorescence was detected. 8-d and older cells that expressed VDCC also displayed high GFP fluorescence intensities.
soldipine more clearly, the mean current for peak $I_{Ca}$ before and after addition of the drug is shown (Fig. 6 A, 1 and 2, dotted line) in the time course (Fig. 6 A, right). The biophysical and pharmacological characteristics excluded that functional T-type and/or the skeletal muscle–specific slow-activating $Ca^{2+}$ current reported for ES cell–derived skeletal myocytes (Rohwedel et al., 1994) were expressed in GFP-positive precursor cells.

Next, we investigated the regulation of $I_{Ca}$ in these cardiac precursor cells. Superfusion with forskolin (1 mM), a selective activator of the adenylyl-cyclase, did not result in an increase of $I_{Ca}$ (Fig. 6 B) in 7-d-old cells, indicating that the cAMP-dependent pathway was not yet functional. A characteristic property of the L-type $Ca^{2+}$ channel is the increase in current amplitude upon phosphorylation by PKA (Osterrieder et al., 1982). Therefore, we tested whether $I_{Ca}$ could be stimulated by dialysis with the catalytic subunit of PKA in 7-d-old cardiac precursor cells. The amplitude of $I_{Ca}$ measured after 5 min cell dialysis with the catalytic subunit of PKA was normalized to the value obtained after 1 min. As seen in Fig. 6 D, four out of four cells tested displayed an increase of peak $I_{Ca}$, the average increase of peak $I_{Ca}$ amounts to 1.7-fold. This is also reflected in the time course of peak $I_{Ca}$ (Fig. 6 C, right; note the linear regression superimposed on the time course). In control cells, either stable $I_{Ca}$ amplitudes or run down of $I_{Ca}$ was observed ($n = 5$; Fig. 6 D).

**Functional Ryanodine-sensitive $Ca^{2+}$ Stores Are Detected Later than $I_{Ca}$ in Most Early Stage Cardiomyocytes; IP$_3$ Receptors and the Sarco-/Endoplasmic $Ca^{2+}$-ATPase Are Found during All Differentiation Stages**

For the investigation of functional ryanodine-sensitive $Ca^{2+}$ stores, caffeine (10 mM) was applied on GFP-positive cells through a puffer pipette. Because of the close correlation between GFP fluorescence intensity and VDCC...
expression (Fig. 4C), only cells with GFP intensities larger than 60 counts were chosen for these experiments. As shown in Fig. 7, A and C, most of the GFP-positive cells showed no detectable caffeine responses at 8/9 d. Within the following 2 d, there was a clear increase in the percentage of responding cells in these early, GFP-expressing cardiomyocytes. As depicted in Fig. 7B, application of caffeine leads to a rise of $[Ca^{2+}]_{i}$ before (234 ± 36 nM) and after superfusion with high K+/BayK8644 solution (1,993 ± 684 nM, $n = 5$, 10/11d). Most of the GFP-positive cells at 9 d express functional VDCC but not ryanodine-sensitive Ca$^{2+}$ stores, whereas 24 h later most of the GFP-positive cells coexpress both (Fig. 7C).

We tested also for the expression of IP$_3$-sensitive Ca$^{2+}$ stores by dialyzing voltage-clamped ES cells and EB-derived cardiomyocytes of different stages with IP$_3$ (100 μM) and fura-2 (125 μM) (Fig. 8, right panels). To avoid the activation of Ca$^{2+}$ influx pathway(s) (holding potential −80 mV), the cells were superfused with nominally Ca$^{2+}$-free solution. Cells of various differentiation stages (ES cells, 5, 7, and 9 d, $n = 4$ for each differentiation stage) were examined and responded to IP$_3$ perfusion with an increase of the 360/390-nm ratio 10–20 s after establishment of the whole-cell configuration (Fig. 8). There was no significant difference in the response between the various stages of development or between GFP-positive and -negative cells (data not shown). Cell dialysis with fura-2 but without IP$_3$ in the patch pipette resulted in all cells tested ($n = 5$) in a decrease of the 360/390-nm ratio (Fig. 8, right panels, insets), probably because of a lowering of resting $[Ca^{2+}]_{i}$ caused by the high concentration of exogenous buffers added to the cell (Neher and Augustine, 1992). Application of the selective Ca$^{2+}$-ATPase inhibitor Tg (1 μM) (Thastrup et al., 1990) resulted in GFP-positive as well as -negative cells of all differentiation stages tested (0–9 d) in a fast increase of $[Ca^{2+}]_{i}$ (Fig. 8, left panels). In ES cells, this increase consisted of a transient and a gadolinium (Gd$^{3+}$)-sensitive sustained phase (Fig. 8A, left; $n =$...
promoter was chosen because transcripts for cardiac interfered on ES cell–derived cardiomyocytes. The GFP did not in-
were detected as early as on E7.5 in the developing murine
transfection ES cell lines, where the GFP expression was
under control of the cardiac-specific human cardiac
promotion (Minty and Kedes, 1986; Pari et al., 1991). The
promoter has been shown to be cardiac specific and
in EBs (Metzger et al., 1996). Since the cardiac precursor cells still lack the character-
istics typical for cardiomyocytes. (c) All GFP-positive precursor cells showed immunostaining for
heart (Sassoon et al., 1988; Lyons et al., 1991). Accordingly, the activity of the LacZ reporter gene under control of the (−440 to +6) segment of the human cardiac α-actin promoter has been shown to be cardiac specific and
switched on before the onset of spontaneous contractions in EBs (Metzger et al., 1996).

The pattern of GFP fluorescence as well as the overlap between GFP expression and spontaneous contractions indicated the specificity, which was further confirmed by immu
encytochemistry. It is well known from the literature that cardiac α-actin and skeletal α-actin are coexpressed in both cardiac and skeletal muscle during embryonic develop-
(Sassoon et al., 1988; Alonso et al., 1990; Lyons et al., 1991). However, the GFP-positive precursor cells in
our experiments did clearly not comprise skeletal muscle cells for the following reasons: (a) the Ca2+
 currents determined in these cells displayed fast activation kinetics, which clearly differed from the slow activation kinetics typical for the skeletal Ca2+ current. Moreover, T-type Ca2+ currents were excluded because of the current–volt-
age relationship, pharmacology, and PKA-dependent phosphorylation. (b) GFP-positive cells of later developmental stages displayed electrophysiological as well as morpho-
logical characteristics typical for cardiomyocytes. (c) All GFP-positive precursor cells showed immunostaining for
ANP, which is known to be expressed early during cardio-
myogenesis, but not in skeletal myocytes (Miller-Hance et al., 1993; Hescheler et al., 1997). Because of the funda-
mental role of VDCC and Ca2+ storage organelles for
cardiac function, their functional expression was investigated in these early GFP-positive cardiomyocytes. Many studies

Discussion
The main goal of the present study was the functional characterization of cardiomyocytes before the initiation of contraction. In particular, we investigated the functional expression of cellular components playing a key role for cardiac function, i.e., L-type Ca2+ channels, Ca2+ release sites, and Ca2+ pumps.

Since the cardiac precursor cells still lack the characteristic cross striation and spontaneous contractions, we have used the in vivo fluorescent reporter gene GFP for the identification of these early cardiomyocytes. For this purpose, we have used the ES cell system for the differen-
tiation of cardiomyocytes (Doetschman et al., 1985; Wobus et al., 1991; Westfall et al., 1997) and established stably transfect ES cell lines, where the GFP expression was under control of the cardiac-specific human cardiac α-actin promoter (Minty and Kedes, 1986; Pari et al., 1991). The stable GFP expression has proven particularly helpful for our investigation since it allowed the identification of GFP-positive cells even very early during development. As reported for transgenic mice, where (E)GFP expression was under control of the ubiquitous β-actin promoter (Ikawa et al., 1995; Okabe et al., 1997), (E)GFP did not interfere on ES cell–derived cardiomyocytes. The α-actin promoter was chosen because transcripts for cardiac α-actin were detected as early as on E7.5 in the developing murine

Figure 7. Temporal correlation between the functional expression of VDCC and ryanodine-sensitive Ca2+ stores using Ca2+ imaging. ES cell–derived cells of different developmental stages were first tested for their GFP fluorescence intensity and subsequently for the functional expression of VDCC with superfusion of high K+/BayK8644 or for ryanodine-sensitive stores with application of caffeine (10 mM) through a puffer pipette. (A) Representative experiment of a GFP-positive 8-d-old cell, which does not respond to caffeine (arrows indicate start of application, duration 7 s) but displays a [Ca2+]i increase upon high K+/BayK8644 perfusion. (B) An 11-d-old GFP-positive cell responds to caffeine (arrows) and high K+/BayK8644 with a large transient and a smaller, more sustained rise of [Ca2+]i, respectively, indicating the functional expression of ryanodine-sensitive Ca2+ stores and VDCC. The depolarization-induced [Ca2+]i rise is larger and faster inactivating than in 8-d-old cells. (C) The correlation between caffeine and VDCC expression, tested in different cells during various differentiation stages. For this analysis, only cells with GFP fluorescence intensities (60 counts were selected). In most of the early stage cardiomyocytes the functional expression of VDCC occurs before ryanodine-sensitive Ca2+ stores.

5), pointing towards activation of a Ca2+ influx pathway. In contrast, the Tg-induced rise of [Ca2+]i in cardiac precursor cells (Fig. 8 B, left; n = 5) was only transient.
have been performed on later embryonic and neonatal mammalian cardiomyocytes, where expression and biophysical characteristics of VDCC and Ca\textsuperscript{2+} handling proteins differed relatively little from terminally differentiated cardiomyocytes (Josephson and Sperelakis, 1989; Masuda and Sperelakis, 1993; Davies et al., 1996; Takano and Noma, 1997). However, almost no functional data are available on very early mammalian cardiomyocytes before E11. Therefore, the ES cell differentiation system in combination with cardiac \alpha-actin promoter–driven GFP expression allowed the identification and functional characterization of cardiomyocytes before beating. Patch clamp studies demonstrated the expression of L-type Ca\textsuperscript{2+} channels at very low density 1 d after plating (7 d). In contrast to embryonic chicken cardiomyocytes, where a decrease in I\textsubscript{Ca} density during development was reported (Tohse et al., 1992), I\textsubscript{Ca} was blocked completely by nisoldipine making an involvement of additional Ca\textsuperscript{2+} handling proteins at very low density 1 d after plating (7 d). In contrast, application of Tg in a cardiac precursor cell (7 d) resulted in a transient rise of [Ca\textsuperscript{2+}]i. The expression of IP\textsubscript{3}-sensitive Ca\textsuperscript{2+} stores was tested by intracellular dialysis of ES cell–derived cells during different stages of development with IP\textsubscript{3} (100 \mu M) and the Ca\textsuperscript{2+} indicator fura-2 (125 M) through patch-pipette (right panels). Changes in [Ca\textsuperscript{2+}]i were monitored using measurements of the 360/390 ratio. Establishment of the classic whole-cell configuration (arrow) evoked in ES cells (A) and 7-d-old cardiomyocytes (B) a fast increase of the 360/390 ratio because of an increase of [Ca\textsuperscript{2+}]i, indicating the functional expression of IP\textsubscript{3}-sensitive stores. In control experiments, omission of IP\textsubscript{3} from the pipette solution evoked a decrease of the 360/390 ratio (insets, identical calibration as for IP\textsubscript{3} experiments).

Figure 8. Functional expression of the sarcoplasmic Ca\textsuperscript{2+}-ATPase and IP\textsubscript{3}-sensitive Ca\textsuperscript{2+} stores in ES cells and ES cell–derived cardiac precursor cells. The expression of the sarcoplasmic Ca\textsuperscript{2+}-ATPase was investigated by addition of the selective antagonist Tg (1 \mu M) (left panels). (A) Tg evoked a sustained increase of [Ca\textsuperscript{2+}]i in ES cells, indicating activation of a capacitative Ca\textsuperscript{2+} influx pathway. This was confirmed by application of Gd\textsuperscript{3+} (1 \mu M), which resulted in a fast decline of elevated [Ca\textsuperscript{2+}]i, to control levels. (B) In contrast, application of Tg in a cardiac precursor cell (7 d) resulted in a transient rise of [Ca\textsuperscript{2+}]i. The expression of IP\textsubscript{3}-sensitive Ca\textsuperscript{2+} stores was tested by intracellular dialysis of ES cell–derived cells during different stages of development with IP\textsubscript{3} (100 \mu M) and the Ca\textsuperscript{2+} indicator fura-2 (125 M) through patch-pipette (right panels). Changes in [Ca\textsuperscript{2+}]i were monitored using measurements of the 360/390 ratio. Establishment of the classic whole-cell configuration (arrow) evoked in ES cells (A) and 7-d-old cardiomyocytes (B) a fast increase of the 360/390 ratio because of an increase of [Ca\textsuperscript{2+}]i, indicating the functional expression of IP\textsubscript{3}-sensitive stores. In control experiments, omission of IP\textsubscript{3} from the pipette solution evoked a decrease of the 360/390 ratio (insets, identical calibration as for IP\textsubscript{3} experiments).
lations in membrane potential are registered earlier than contractions in chick (Fujii et al., 1981) and rat (Hirota et al., 1985) embryonic cardiomyocytes, despite the presence of contractile proteins. This could be due to the lack of CICR, the fundamental process responsible for excitation–contraction coupling (Fabio, 1985; Barcenas-Ruiz and Wier, 1987; du Bell and Houser, 1987; Nabauer et al., 1989). In the literature, electromechanical coupling in the fetal heart (late embryonic stage) is suggested to be largely dependent on transsarcolemmal Ca\(^{2+}\) influx, rather than Ca\(^{2+}\) released from the SR (Naylor and Fassold, 1977; Mahony and Jones, 1986; Kitzner and Friedman, 1989; Chin et al., 1990). In addition, the SR was found to be morphologically smaller in neonatal ventricular cardiomyocytes (Olivetti et al., 1980), and the number of ryanodine receptors in fetal rat ventricular cardiomyocytes (E22) was reduced as compared with adult rat ventricular cardiomyocytes (Ramesh et al., 1995). Nevertheless, Su and Chang (1993) report caffeine-induced contractions in fetal hearts. Accordingly, a spatial coassociation between ryanodine receptors and VDCC has been reported for chick cardiomyocytes early during development (Sun et al., 1995; Flucher and Franzini-Armstrong, 1996). Recently, embryonic lethality between E10.5–11.5 of mice carrying a gene inactivation of the ryanodine 2 receptor was described (Takeshima et al., 1998). While the hearts of mutant mice started to spontaneously contract at E9.5, severe morphological changes of the SR and the mitochondria were detected. The authors suggest that Ry-2 may not be required for excitation–contraction coupling at this early embryonic stage but play a crucial role for Ca\(^{2+}\) homeostasis. Our data fit nicely in since we demonstrate herewith functional ryanodine-sensitive Ca\(^{2+}\) stores in early stage cardiomyocytes, and we provide at least indirect evidence for a role of ryanodine-sensitive Ca\(^{2+}\) receptors/stores for the establishment of contractile activity.

Therefore, we report to the best of our knowledge for the first time the functional characterization of cardiomyocytes before the beginning of spontaneous contractions. In these cardiac precursor cells, the VDCC are already functionally expressed and can be stimulated via protein kinase A–dependent phosphorylation. At this stage, IP\(_3\) stores as well as sarcomplasmic Ca\(^{2+}\)-ATPases are already functional, while caffeine-sensitive ryanodine receptors/stores are not yet expressed. Interestingly, even though ryanodine stores may not play such an important role in excitation–contraction coupling at this early stage, in our system their functional expression coincides with the initiation of contractions. In the future, it will be interesting to address the role of VDCC as well as of ryanodine receptors for cardiomyogenesis by using selective pharmacological blockers during different stages of ES cell–derived cardiomyogenesis.

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