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Transgenic-Cloned Pigs Systemically Expressing Red Fluorescent Protein, Kusabira-Orange

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Abstract

Genetically engineered pigs with cell markers such as fluorescent proteins are highly useful in lines of research that include the tracking of transplanted cells or tissues. In this study, we produced transgenic-cloned pigs carrying a gene for the newly developed red fluorescent protein, humanized Kusabira-Orange (huKO), which was cloned from the coral stone *Fungia concinna*. The nuclear transfer embryos, reconstructed with fetal fibroblast cells that had been transduced with huKO cDNA using retroviral vector DΔNsap, developed efficiently *in vitro* into blastocysts (28.0%, 37/132). Nearly all (94.6%, 35/37) of the cloned blastocysts derived from the transduced cells exhibited clear huKO gene expression. A total of 429 nuclear transfer embryos were transferred to four recipients, all of which became pregnant and gave birth to 18 transgenic-cloned offspring in total. All of the pigs highly expressed huKO fluorescence in all of the 23 organs and tissues analyzed, including the brain, eyes, intestinal and reproductive organs, skeletal muscle, bone, skin, and hoof. Furthermore, such expression was also confirmed by histological analyses of various tissues such as pancreatic islets, renal corpuscles, neuronal and glial cells, the retina, chondrocytes, and hematopoietic cells. These data demonstrate that transgenic-cloned pigs exhibiting systemic red fluorescence expression can be efficiently produced by nuclear transfer of somatic cells retrovirally transduced with huKO gene.

Introduction

PIGS HAVE BEEN INCREASINGLY USED as large animal models in biomedical research (Lunney, 2007; Petters, 1994; Prather et al., 2003). For example, as they are comparatively larger than rodents, various surgical procedures that have been performed on humans can be applied to the pig (for review, see Lunney, 2007). The anatomical and physiological similarities of pigs and humans also offer a potential solution to the problem that murine studies cannot necessarily be extrapolated to humans (Lunney, 2007; Petters, 1994; Prather et al., 2003). Thus, genetically engineered pigs produced as human disease models are expected to cover the shortcomings of rodent models (Petters et al., 1997; Rogers et al., 2008). Furthermore, in order to render stem and progenitor cell-based therapies more feasible for the treatment of various intractable disorders, research must be conducted not only in rodent animal models, but also in large animal models such as pigs (Lunney, 2007; Matsumoto et al., 2007).

Under these circumstances, genetically engineered animals with cell markers such as fluorescent proteins are highly useful in lines of research, which include the tracking of transplanted cells or tissues (Hadjantonakis and Nagy, 2001; Murakami and Kobayashi, 2005; Okabe et al., 1997; Yin et al., 2007). Transgenic pigs expressing enhanced green fluorescent protein (EGFP) have been produced by various re-

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search groups (Cabot et al., 2001; Hofmann et al., 2003; Hyun et al., 2003; Lai et al., 2002; Naruse et al., 2005; Park et al., 2002; Watanabe et al., 2005; Webster et al., 2005; Whitelaw et al., 2004; Yong et al., 2006). On the other hand, rodents expressing not only EGFP but also various other markers have been produced, making rodents a useful model for a wide range of research (Luche et al., 2007; Murakami and Kobayashi, 2005; Sato et al., 2003; Vintersten et al., 2004). Indeed, red fluorescent protein (RFP) variants with longer excitation/emission wavelengths than EGFP offer benefits for genetically and spectrally distinct imaging of multiple cell populations in complex tissues (Long et al., 2005). Webster et al. (2005) reported the production of transgenic pigs that simultaneously express DsRed (DsRed2; Long et al., 2005) in addition to EGFP. However, the effect of using DsRed, which is highly cytotoxic (Long et al., 2005), in transgenic pigs has not been clarified.

In the present study, we produced transgenic-cloned pigs carrying the huKO gene (Karasawa et al., 2004), a newly developed RFP. Kusabira-Orange, which was cloned from the coral stone *Fungia concinna* ("Kusabira-Ishi" in Japanese), yields an orange-red fluorescence in dimeric form with a 558/583 nm excitation/emission maxima, respectively (Karasawa et al., 2004). We performed somatic cell nuclear transfer (SCNT) using fetal fibroblast cells that were transduced with the huKO gene by a retroviral vector. The production efficiency, embryonic development, and *in vitro* fluorescence expression of the cloned embryos were investigated. We were able to successfully produce transgenic-cloned pigs with a high efficiency by transfer of SCNT embryos. In addition, systemic red fluorescence expression was confirmed in all cloned pigs produced in the present study.

Materials and Methods

Animal care and chemicals

All of the animal experiments in this study were approved by the Institutional Animal Care and Used Committee of Meiji University (IAUCU-05-003). Chemicals were purchased from Sigma Chemical Co. (St. Louis, MO) unless otherwise indicated.

Construction of DΔNsap expressing huKO gene

The retroviral vector DΔNsap was constructed from previously reported vector, GCDsap (Hamanaka et al., 2007). Briefly, the binding site for Ying-Yang1 (YY1) transcription factor (Wahlers et al., 2002), referred to as the negative control region (NCR), in the PCC4 cell-passaged myeloproliferative sarcoma virus (PCMV)-derived LTR of GCDsap (Hamanaka et al., 2007) was abolished by site-directed mutagenesis using a PCR technique (Fig. 1A). *Nco*I–*Not*I fragments of the huKO cDNA were inserted into the *Nco*I–*Not*I digested vector to generate DΔNsaphuKO (Fig. 1A). The vector was converted to the corresponding retroviruses packaged in the vesicular stomatitis virus G protein (VSV-G) envelope by transduction into 293gpg cells, as described elsewhere (Suzuki et al., 2002a). The virus titer of DΔNsaphuKO was approximately 2.0×10^7 infectious units (I.U.)/mL, as assessed in Jurkat cells. No replication-competent retrovirus was detected.

Transduction of huKO into nuclear donor cells

In this study, the huKO cDNA synthesized by humanizing the original amino acid sequence of Kusabira-Orange gene (Karasawa et al., 2004) was used as a fluorescent marker.

A primary culture of fetal fibroblasts was established from a day 30 porcine female fetus (Crossbred: Large White/Landrace × Duroc) following the standard procedure (Freshney, 2005; Kurome et al., 2003). Established cells were cultured in Dulbecco Modified Eagle medium (DMEM; D6546) supplemented with 15% fetal bovine serum (FBS; Code No. 12303C, JRH Biosciences, Lexena, KS) and cryopreserved after two to six passages. For transduction, the frozen–thawed cells suspended in 5 mL Knockout DMEM (Invitrogen Corp., Carlsbad, CA) supplemented with 10% (v/v) FBS (ES Cell Qualified FBS, Code No. 16141-079, Invitrogen) at the concentration of 1×10^6/mL were transferred into a gelatin-coated six-well dish and transduced with the DΔNsaphuKO by adding 30 μL (multiplicity of infection = 0.12) of the virus supernatant to the culture. At 48 h after transduction, the cells were washed with PBS twice and transferred into a new six-well dish containing the same medium. The transduced cells were cryopreserved after 15–16 passages.

In vitro *maturation of recipient oocytes*

Porcine ovaries were collected at a local abattoir and transported to the laboratory in PBS containing 75 μg/mL potassium penicillin G, 50 μg/mL streptomycin sulfate, 2.5 μg/mL amphotericin B, and 0.1% (v/v) polyvinyl alcohol (PVA). Cumulus–oocyte complexes were collected from the ovarian antral follicles (3.0 to 6.0 mm in diameter) by aspirating with a 10-mL syringe and 20 G hypodermic needle, and those with at least three layers of compacted cumulus cells were selected and cultured in NCSU23 medium (Petters and Wells, 1993) supplemented with 0.6 mM cysteine, 10 ng/mL epidermal growth factor, 10% (v/v) porcine follicular fluid, 75 μg/mL potassium penicillin G, 50 μg/mL streptomycin sulfate, 10 IU/mL eCG (ASKA Pharmaceutical. Co., Tokyo, Japan), and 10 IU/mL hCG (ASKA Pharmaceutical) at 38.5°C in a humidified atmosphere of 5% CO_2 in air for 22 h. Then, oocytes were cultured for an additional 22 h without eCG and hCG (Funahashi and Day, 1993). *In vitro* matured (IVM) oocytes with expanded cumulus cells were treated with 1 mg/mL of hyaluronidase dissolved in Tyrode lactose medium containing 10 mM HEPES and 0.3% (w/v) polyvinylpyrrolidone (HEPES-TL-PVP), and separated from the cumulus cells by gentle pipetting. Oocytes with an evenly granulated ooplasm and an extruded first polar body were selected for the subsequent experiments.

Nuclear transfer of huKO-transduced fibroblasts into IVM oocytes

Somatic cell nuclear transfer of porcine fetal fibroblasts into enucleated oocytes was performed as described elsewhere (Kurome et al., 2003; Tomii et al., 2005; Yin et al., 2002). Oocytes were cultured in NCSU23 medium supplemented with 0.1 μg/mL demecolcine, 0.5 M sucrose (Nacalai Tesque, Inc., Kyoto, Japan) and 4 mg/mL BSA (Fruction V, A-4919) for 0.5 to 1 h, and enucleated by aspirating the first polar body and adjacent cytoplasm using a beveled pipette (30 μm

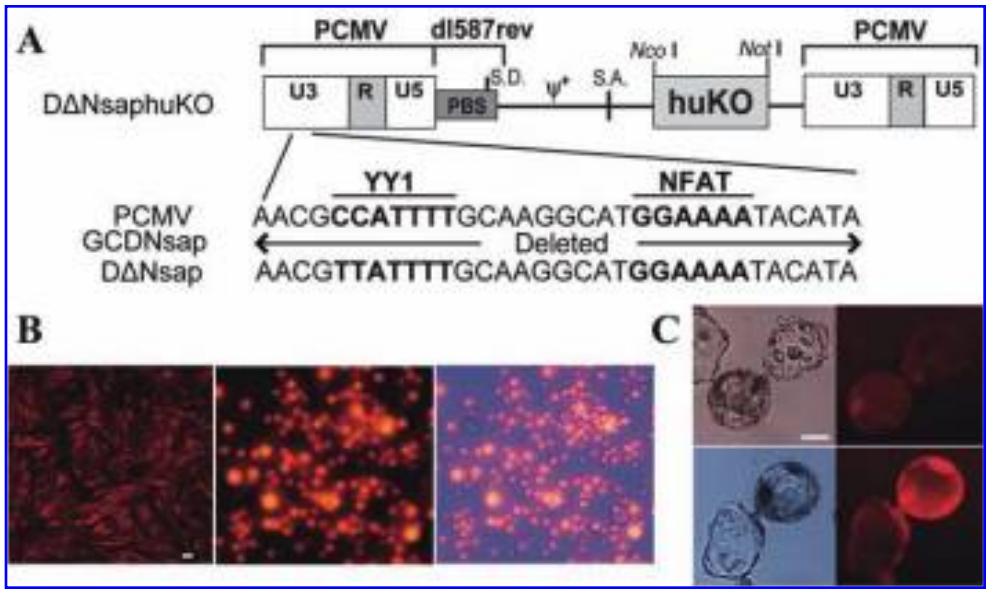

FIG. 1. Retroviral vector construct, transduced nuclear donor cells and cloned blastocysts reconstructed with transduced cells. (**A**) Structure of the retroviral vector DΔNsaphuKO. DΔNsap has the PCMV derived LTR in which the binding site for YY1 (CCATTTT) was abolished by site-directed mutagenesis with PCR while the NFAT binding site (GGAAAA) is still functional. In contrast, GCDNsap from which DΔNsap has been generated has the PCMV-derived LTR that lacks both of the binding sites for YY1 and NFAT. The *Nco*I–*Not*I fragments containing huKO cDNA were cloned into the corresponding site of the vector. A dark box represents the primer-binding site (PBS) derived from the dl587rev. Abbreviations present in the vector are labeled as follows; PCMV: PCC4-cell passaged myeloproliferative sarcoma virus, Ψ^+: packaging signal, S.D and S.A: splice donor and acceptor sequences. (**B**) Porcine fetal fibroblast cells expressing huKO after retroviral transduction (left panel), and the nuclear donor cells (middle panel) used for cloning the pigs. A merged picture (right panel) shows that over 80% of the donor cells were positive for huKO expression. Scale bar = 20 μm. (**C**) Cloned blastocysts (upper and lower left panels) were produced by nuclear transfer of the transduced cells. Note that the huKO expression level of these embryos varies (upper and lower right panels). Scale bar = 50 μm.

in diameter) in HEPES-TL-PVP containing 0.1 μg/mL demecolcine, 5 μg/mL cytochalasin B (CB), and 10% FBS. When a protrusion was observed on the surface of an oocyte, it was removed along with the polar body. Enucleation was confirmed by staining the cytoplasts with 5 μg/mL bisbenzimide (Hoechst 33324).

Porcine fetal fibroblasts transduced with the huKO cDNA and control, nontransduced cells, which had been respectively cryopreserved after 15–16 or 5–6 passages, were used as nuclear donors. After thawing, the cell cycles of the donor cells were synchronized by serum starvation (0.5% ES Cell Qualified FBS for transduced cells and 0.5% FBS for control cells) for 48 h. A single donor cell was inserted into the perivitelline space of an enucleated oocyte. The donor cell–oocyte complexes were suspended in mannitol solution (280 mM, pH 7.2) containing 0.15 mM $MgSO_4$, 0.01% (w/v) PVA and 0.5 mM HEPES and held between two electrode needles. Membrane fusion was induced with a somatic hybridizer (SSH-1; Shimadzu, Koyto, Japan) by applying a single direct current (DC) pulse (187 to 200 V/mm, 20 μsec $\times$1) and a pre- and postpulse alternating current (AC) field of 5 V, 1 MHz for 5 sec, respectively. The reconstructed embryos were cul-

FIG. 2. Transgenic-cloned fetus and pigs produced by SCNT of huKO fetal fibroblast cells transduced with huKO gene. A day-47 fetus (**A**) with systemic fluorescence expression (scale bar = 1 cm). Newborn offspring (**B**) and a fully matured gilt (**C**; O18-3, 17-month-old).

tured in the NCSU23 medium with 4 mg/mL BSA for 1 to 1.5 h followed by electrical activation (DC 150 V/mm, 100 μsec $\times$1) and subsequent treatment with 5 μg/mL CB for 3 h to suppress extrusion of the pseudosecond polar body.

Cleavage, blastocyst formation, and expression of huKO gene in the early developmental stage of the cloned embryos were monitored during culture for 7 days. *In vitro* culture of the embryos was performed in 20 μL droplets of modified NCSU23 (Nagashima et al., 2007). On day 7 embryos were examined under fluorescent microscopy (TE-300, Nikon, Tokyo, Japan), and the cell number of blastocysts was also counted after fixation and staining.

Transfer of cloned embryos into recipient pigs

Crossbred (Large White/Landrace $\times$ Duroc) prepubertal gilts weighing from 100 to 105 kg were used as recipients of the embryos. For the induction of estrus, gilts were intramuscularly injected with 1000 IU of eCG (ASKA Pharmaceutical, Tokyo, Japan) followed by 1500 IU of hCG (Kawasaki Mitaka Pharmaceutical. Co., Kawasaki, Japan) 72 h later. Having been cultured in the Porcine Zygote Medium-5 (PZM-5; Functional Peptide Inc., Yamagata, Japan) for 1 to 2 days, embryos with a normal morphological appearance and at the one-cell stage on days 1 and two to eight-cell stage on day 2, were selected and transferred into oviducts of the recipient gilts that had received hCG injection 48 h previously.

Analysis of huKO expression in the transgenic-cloned pigs

Transgenic-cloned offspring were autopsied to collect small snips of 23 organs and tissues in total, including the brain, heart, lung, stomach, intestine, liver, pancreas, spleen, kidney, bladder, ovary, uterus, skin, subcutaneous fat, skeletal muscle, bone (rib), cartilage, synovium, salivary gland, oral mucosa, tongue, eye, and hoof. These tissues were observed under MVX10 fluorescence stereomicroscopy (Olympus, Tokyo, Japan; excitation wavelength: 530–555 nm, absorption filter: 570–625 nm) to examine huKO expression. Paraffin-embedded sections of those organs and tissues were also observed under fluorescence microscopy (Olympus BX52, excitation wavelength: 520–550 nm, absorption filter: 580 nm).

For immunohistochemistry of the brain, cryosections were stained with antidoublecortin (DCX) antibody (polyclonal goat IgG, Santa Cruz Biotechnology Inc., Santa Cruz, CA), antimicrotubule-associated protein (MAP2) antibody (monoclonal mouse IgG, Upstate Co., Charlottesville, VA), anti-ionized calcium binding adaptor protein (Iba1) antibody (polyclonal rabbit IgG, Wako, Osaka, Japan), and antiglial fibrillary acidic protein (GFAP) antibody (polyclonal rabbit IgG; a generous gift from Dr. Haruhiko Akiyama, Psychiatric Research Institute of Tokyo, Tokyo, Japan), followed by staining with FITC-labeled secondary antibody (Hayakawa et al., 2007; Yamada et al., 2004). Images of sections were obtained using an LSM-510 laser-scanning microscope (Carl Zeiss, Oberkochen, Germany).

Expression of huKO gene was analyzed in blood cells and subcutaneous fat tissue of a growing pig (O18-3). Peripheral blood was collected from a 4-month-old transgenic-cloned pig (O18-3). Each hematopoietic lineage grouped by both forward scatter (FSC) and side scatter (SSC) values was analyzed for huKO expression using FACS calibur (Becton Dickinson, San Jose, CA). A small snip of subcutaneous fat tissue collected from the same pig at 7 and 17 months after birth was observed under fluorescence microscopy (BZ-8000, Keyence, Osaka, Japan; excitation wavelength: 525–540 nm, absorption filter: 605–655 nm).

Southern blot analysis

High molecular-weight DNA was isolated from the skin or kidney of the cloned offspring and a control wild-type piglet. Ten micrograms of genomic DNA was digested with *Bam*HI overnight, separated in 1% agarose gel, transferred to a nylon membrane (GE Healthcare UK Ltd., Buckinghamshire, England), and hybridized to [α-^{32}P] CTP labeled huKO cDNA. The restriction enzyme *Bam*HI cuts the vector at one site, and therefore the number of fragments hybridized with the probe is considered to be the number of provirus copies integrated into the host genomes.

Statistical analysis

For proportional data, differences between groups were analyzed using the χ^2 test. For blastocyst cell number data, differences between groups were determined by Student's *t*-test. The level of significance was set at $p < 0.05$.

Results

Production of cloned embryos by nuclear transfer of huKO expressing cells

When the fibroblasts were exposed to the concentrated virus supernatant, approximately 80% of the cells highly ex-

Table 1. *In Vitro* Development and Huko Expression of the Cloned Embryos Reconstructed with Retrovirally Transduced Cells

		Embryonic development (%)			
Donor cells	*Fusion rate*	*Cleaved*	*Blastocysts*	*Cell number in blastocysts (Mean ± SEM)*	*huKO expressing blastocysts (%)*
huKO-PFF	132/151 (87.4)	78/132 (59.1)	37/132 (28.0)[a]	48.6 ± 4.8	35/37 (94.6)
PFF	134/147 (91.2)	86/134 (64.2)	20/134 (14.9)[a]	42.3 ± 4.9	0/20 (0)

huKO-PFF, porcine fetal fibroblast cells transduced with DΔNsaphuKO; PFF, nontransduced fetal fibroblast cells.
[a]$p < 0.05$.

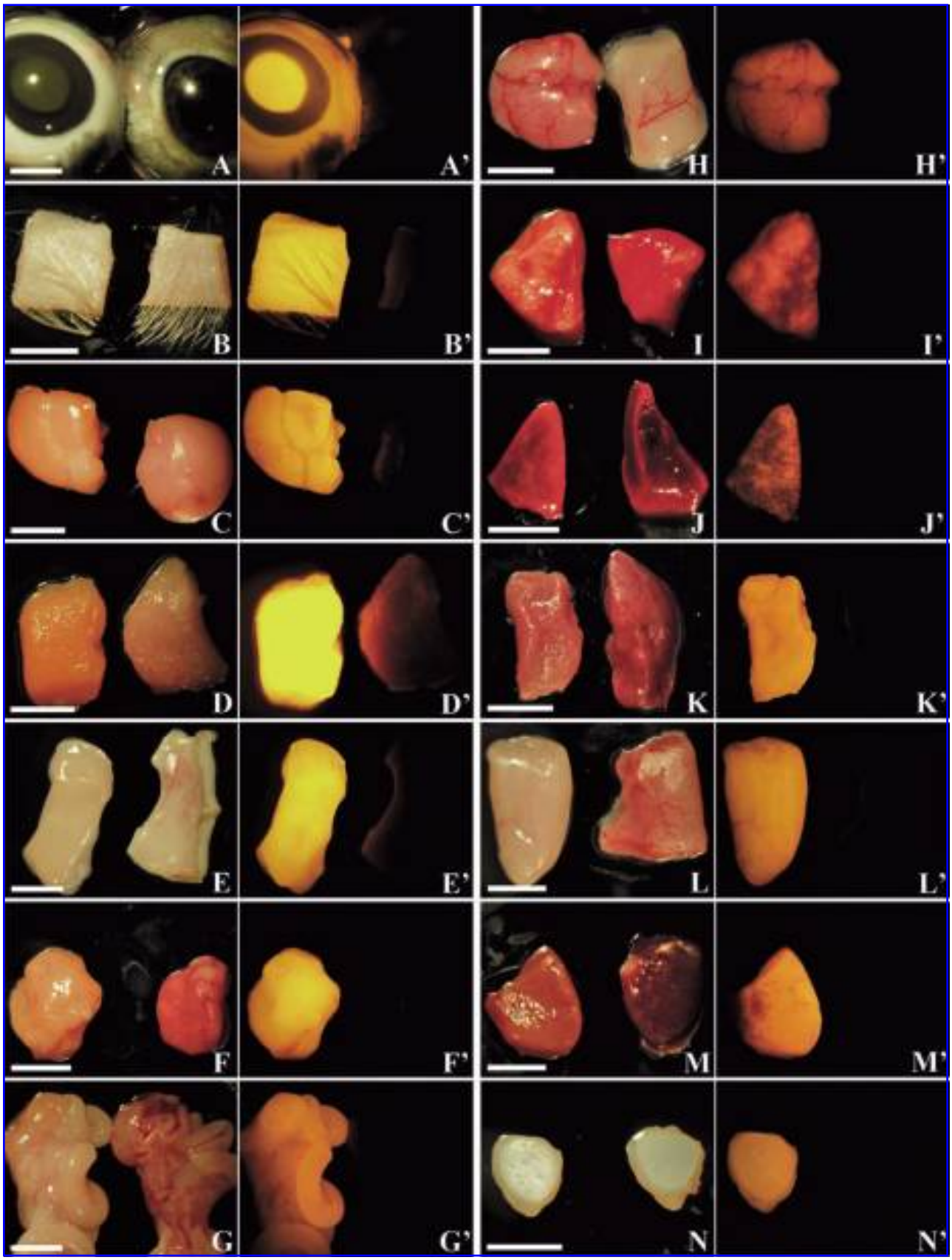

FIG. 3. Systemic expression of huKO in transgenic-cloned pigs. (**A–N)** Bright-field stereomicroscopic images of tissues from a transgenic-cloned offspring (left) and nontransgenic control (right). (**A′–N′)** Fluorescence stereomicroscopic images demonstrate that tissues from the transgenic-cloned pig (left) exhibit distinctive fluorescence, while none of the control tissues (right) has background autofluorescence. eye (**A**,**A′**); skin (**B**,**B′**); salivary gland (**C**,**C′**); skeletal muscle (**D**,**D′**); stomach (**E**,**E′**); pancreas (**F**,**F′**); reproductive tract and ovary (**G**,**G′**); brain (**H**,**H′**); lung (**I**,**I′**); liver (**J**,**J′**); heart (**K**,**K′**); intestine (**L**,**L′**); kidney (**M**,**M′)**; bone[rib] (**N**,**N′**). Scale bar = 5 mm.

pressed huKO (Fig. 1B), and such expression was maintained in porcine nuclear transfer embryos reconstructed with the transduced fibroblasts (Fig. 1C). As shown in Table 1, nearly all (94.6%, 35/37) of the cloned blastocysts derived from the transduced cells clearly exhibited evident huKO expression, although the level of fluorescence varied among the embryos (Fig. 1C). Efficiency of cell fusion and early cleavage of the cloned embryos using transduced cells as nuclear donors was comparable to that with control nontransduced fibroblasts (Table 1). Furthermore, the rate of *in vitro* blastocyst formation of the cloned embryos reconstructed with transduced cells was rather higher than that of control embryos derived from nontransduced cells (Table 1).

Development of transgenic-cloned pigs transduced with huKO gene

Having determined that the expression of huKO gene had very few, if any, detrimental effects on the development of porcine embryos per se, the embryos were transferred into the oviducts of five estrus-synchronized recipient gilts. Three fetuses (day 47) were obtained from one recipient into which 76 cloned embryos had been transferred (Fig. 2A). When 429 of the nuclear transfer embryos in total had been transferred to four recipients, all of them became pregnant and gave birth to 18 offspring (Fig. 2B), including four cases of stillbirth. The average body weight and length of these offspring were 1068.2 ± 77.4 g and 22.7 ± 0.7 cm, respectively (mean ± SEM). The production efficiency of the transgenic-cloned offspring and fetuses from the retrovirally transduced cells was 4.2%.

Expression of huKO gene in the entire body of the cloned pigs

Fluorescence stereomicroscopic examination revealed that both the fetuses and offspring highly expressed huKO ubiquitously throughout their entire bodies (Fig. 3). Furthermore, histological analysis of 23 various organs and tissues confirmed the high expression of huKO, although the intensity of expression varied among these organs (Fig. 4). Expression of huKO fluorescence at the red wavelength could be clearly detected in the liver without any interference from autofluorescence (Fig. 3J, J′, Fig. 4J, J′). Interestingly, the pancreatic islets (Fig. 4I, I′) and renal corpuscles (Fig. 4K, K′) exhibited markedly prominent red fluorescence compared to the surrounding tissues. Prominent expression of huKO was also detected in other tissues, such as the crystalline lens (Fig. 3A, A′, Fig. 4 A, A′) and the acinus of the submandibular gland (Fig. 3C, C′, Fig. 4C, C′).

The expression of huKO in neurons and glial cells was observed in immunostaining with neuron- or glia-specific antibodies such as DCX and MAP2 or Iba1 and GFAP, respectively (Fig. 5).

Analysis of peripheral blood cells collected from a 4-month-old transgenic-cloned pig (O18-3) by FACS calibur revealed that huKO was expressed in hematopoietic cells, including granulocytes, monocytes, lymphocytes, and platelets, although the expression of huKO in red blood cells (RBC) was much lower than that of other lineages (Fig. 6).

As shown in Fig. 7, fluorescence expression level of subcutaneous fat tissue observed at 7 months after birth (A, A′) was maintained even at 17 months (B, B′).

Multiple copies of the provirus in cloned pigs

To determine the number of copies of the provirus integrated into the chromosomes of cloned pigs, high molecular-weight DNA was obtained from 12 cloned pigs and hybridized with the huKO cDNA as a probe following digestion with the restriction enzyme *Bam*HI, which cuts the vector at one site. As shown in Figure 8A, Southern blot analysis revealed that each pig had multiple copies of the provirus ranging from 2 to 17, suggesting that cloned pigs developed by nuclear transfer stably maintained the transgene in their chromosomes through ontogenesis and resulted in high expression of huKO in the whole body.

All of the four transgenic pigs showing lower fluorescence expression level were revealed to have fewer copy numbers (2–6) of the provirus (Fig. 8BC, B′C′). In contrast, six other transgenic pigs with higher huKO expression level had higher (≥9) copies of provirus (Fig. 8D–G, D′–G′), except for one with two copies of the transgene.

Discussion

The SCNT approach described here, combined with the retrovirus-mediated gene transfer method, allowed stable expression of the transgene in cloned pigs that were developed from embryos reconstructed with fetal fibroblasts transduced with the huKO cDNA. To the best of our knowledge, this is the first report on the production of transgenic-cloned pigs expressing Kusabira-Orange.

The production efficiency (4.2%) of the transgenic-cloned offspring in this study was comparable to that observed in nuclear transfer experiments using nontransgenic donor cells in previous reports by both our group and other researchers (Kurome et al., 2006; Tomii et al., 2005; Walker et al., 2002). The high clone production efficiency observed was likely ascribable to the preparation of high-quality nuclear donor cells. Drug selection of the transfected nuclear donor cells for a relatively long period of time has been reported to induce chromosomal aberrance (Forsberg et al., 2002; Fujimura et al., 2008; Iguma et al., 2005; Zakhartchenko et al., 2001), resulting in a significant reduction of the birth rate of clones. In contrast, we were able to use retrovirally transduced fetal fibroblasts as the nuclear donor cells without any selection procedures, because more than 80% of the cells had highly expressed huKO after one round of transduction. Retroviral integration into donor cells per se was also unlikely to be toxic, as demonstrated by the fact that 82% (data

FIG. 4. Histological analysis of various tissues from the transgenic-cloned pigs with systemic huKO expression. HE stained (**A**–**P**) and fluorescence microscopy (**A′**–**P′**) of paraffin-embedded serial sections of huKO transgenic-cloned piglets. eye (**A**,**A′**); tongue (**B**,**B′**); salivary gland (**C**,**C′**); intestine (**D**,**D′**); spleen (**E**,**E′**); bladder (**F**,**F′**); uterus (**G**,**G′**); hoof (**H**,**H′**); pancreas (**I**,**I′**); liver (**J**,**J′**); kidney (**K**,**K′**); ovary (**L**,**L′**); subcutaneous fat (**M**,**M′**); cartilage (**N**,**N′**); synovium (**O**,**O′**); hard palate (**P**,**P′**). Note that the islets of Langerhans (**I**,**I′**) and renal corpuscles (**K**,**K′**) indicated by the arrows display prominent red fluorescence compared to the surrounding tissues. Scale bar = 1 cm (**A**); 500 μm (**B**–**H**) and 100 μm (**I**–**P**).

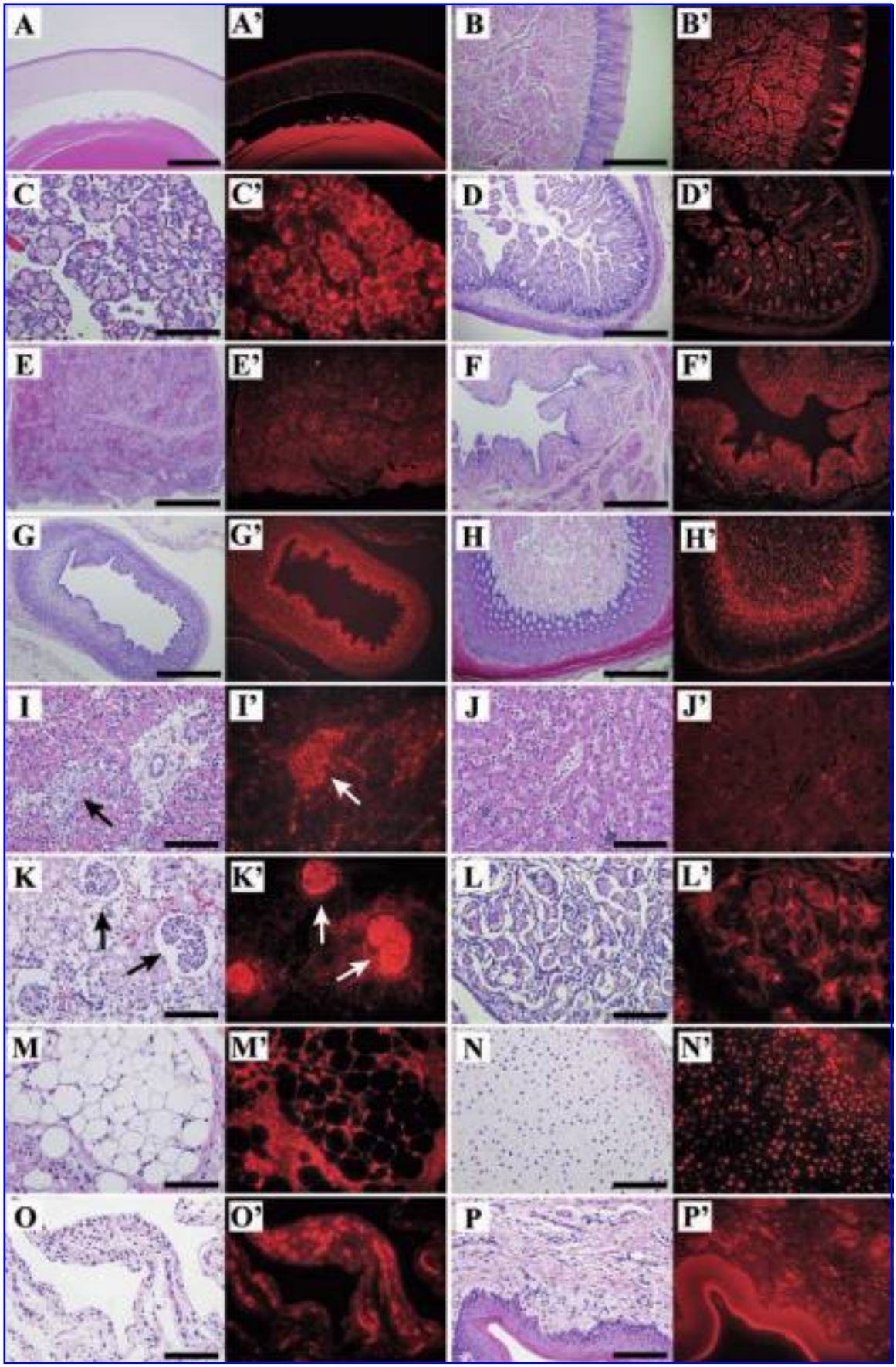

FIG. 4.

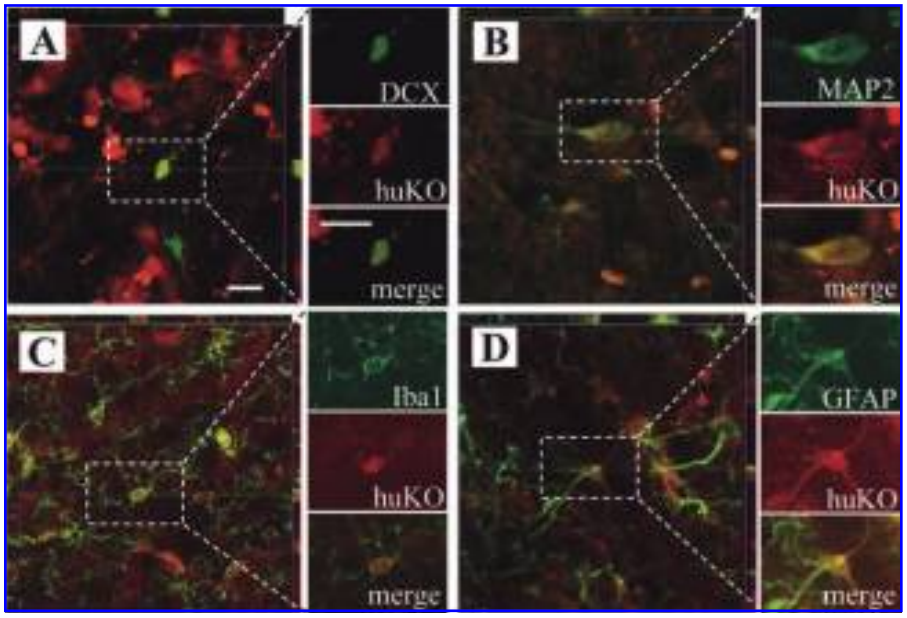

FIG. 5. Immunofluorescent staining of neural cells from huKO transgenic-cloned pigs. To examine huKO expression in neuronal and glial cells, brain tissue sections were examined by immunofluorescent staining and fluorescence microscopy. The boxed insets show that huKO expression was colocalized with DCX (**A**), MAP2 (**B**), Iba1 (**C**), and GFAP (**D**), which are markers for neuron progenitors, mature neurons, microglia, and astrocytes, respectively. Scale bar = 20 μm.

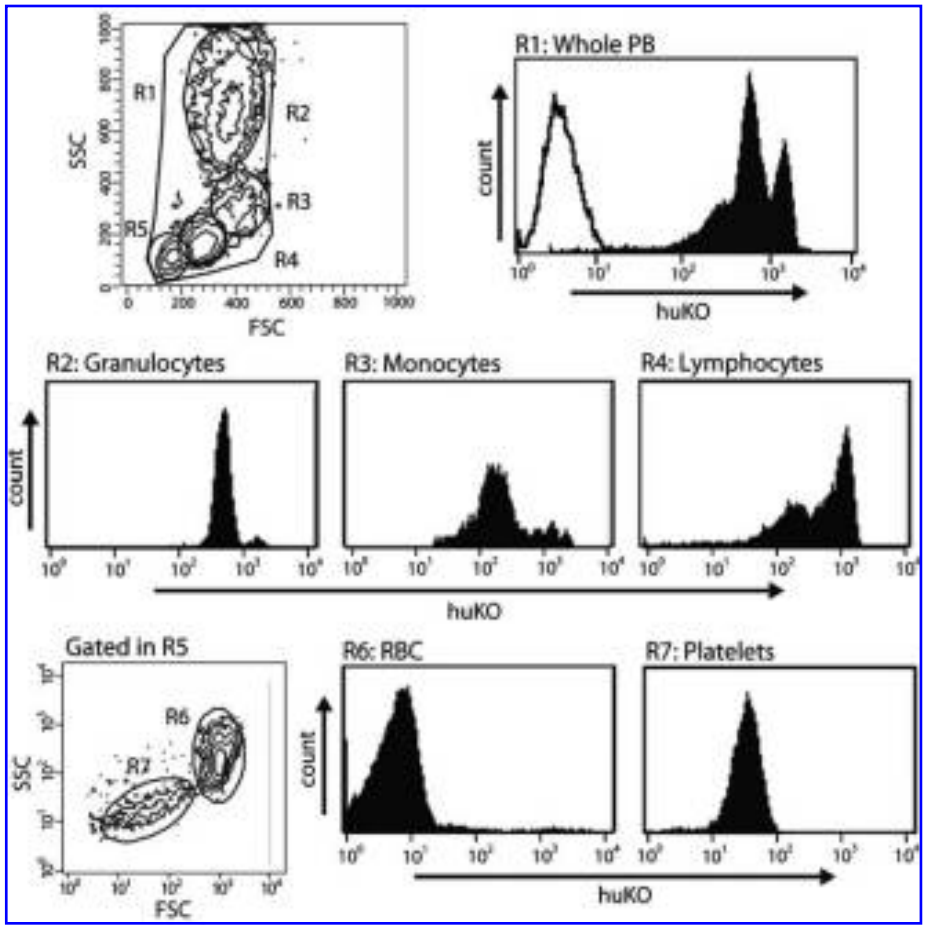

FIG. 6. Expression of huKO in peripheral blood of a transgenic-cloned pig. Peripheral blood was collected from a 4-month-old transgenic-cloned pig (O18-3) and analyzed with FACS calibur. The population of each lineage was classified by both forward scatter (FSC) and side scatter (SSC) values of the flow cytometry. The R6 (RBC) and R7 (platelet) were gated from the R5. Each hematopoietic lineage (R2: granulocytes, R3: monocytes, R4; lymphocytes, R6: RBC, and R7: platelets) in the peripheral blood of the cloned pigs was analyzed in terms of huKO expression.

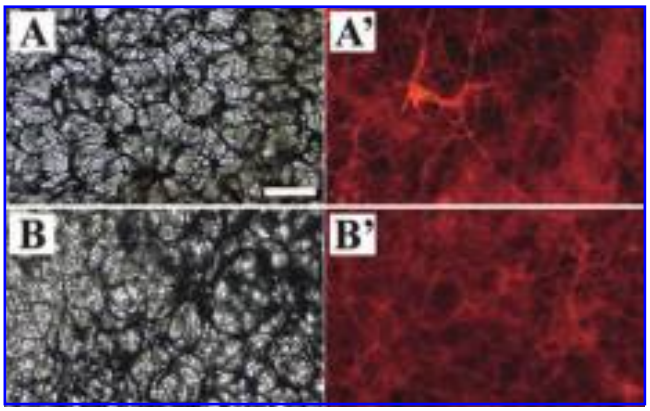

FIG. 7. Expression of huKO in subcutaneous fat tissue of a growing transgenic-cloned pig (O18-3). Bright-field (**A,B**) and fluorescence (**A′,B′**) microscopic image of subcutaneous fat tissue collected at 7 (**A,A′**) and 17 (**B,B′**) months after birth. Scale bar = 200 μm.

not shown) of the transduced cells maintained a normal karyotype.

The successful development of the transgenic-cloned pigs accompanying systemic transgene expression is attributable to the high transduction efficiency of our retroviral vector in fetal fibroblasts, as large numbers of provirus were shown by Southern blot analysis to have been introduced into the genomes. The introduction of multiple proviruses into the host genome is a characteristic of retroviral vectors (Hamanaka et al., 2007).

Production of transgenic large animals expressing fluorescent protein genes after transduction using viral vectors has been reported by a number of research groups (Cabot et al., 2001; Chan et al., 2001; Hofmann et al., 2004). In using these animals for research, it is important to consider the types of tissues or cells in which the transduced gene is expressed. Among the huKO pigs produced in the present study, systemic expression of the transduced gene was confirmed in all the pigs examined. Peripheral blood cells except for RBC collected from one 4-month-old transgenic-cloned pig also maintained the expression of huKO gene. It was also confirmed that fluorescence expression level of subcutaneous fat tissue was maintained by at least 17 months after birth. These data indicate stable transgene expression in a growing transgenic pig produced in this study.

Expression of EGFP transduced into embryonic stem cells with a mouse stem cell virus-based vector has been reported to diminish in the resultant chimeric mice (Cherry et al., 2000). In contrast, by using the retroviral vector GCDNsap (Nabekura et al., 2006), we demonstrated high and continued expression of the transgene in immature cells, such as hematopoietic stem cells (Nabekura et al., 2006), neural stem cells (Suzuki et al., 2002a), and hepatic stem cells (Suzuki et al., 2002b). This vector has the dl587rev-derived primer binding site and PCMV-derived LTR in which a 71-bp fragment containing the NCR, a binding site for the transcriptional repressor YY1(Wahlers et al., 2002), was removed by digestion with restriction enzymes and a cloning method (Hamanaka et al., 2007). However, recent studies have shown that the fragment removed by this method also contains a binding site for nuclear factor of activated T cells (NFAT), which is important for maintaining the transcription level of the provirus (Wahlers et al., 2002; Wang et al., 2003). Therefore, in the construction of DΔNsap, the site for YY1 was abolished by site-directed

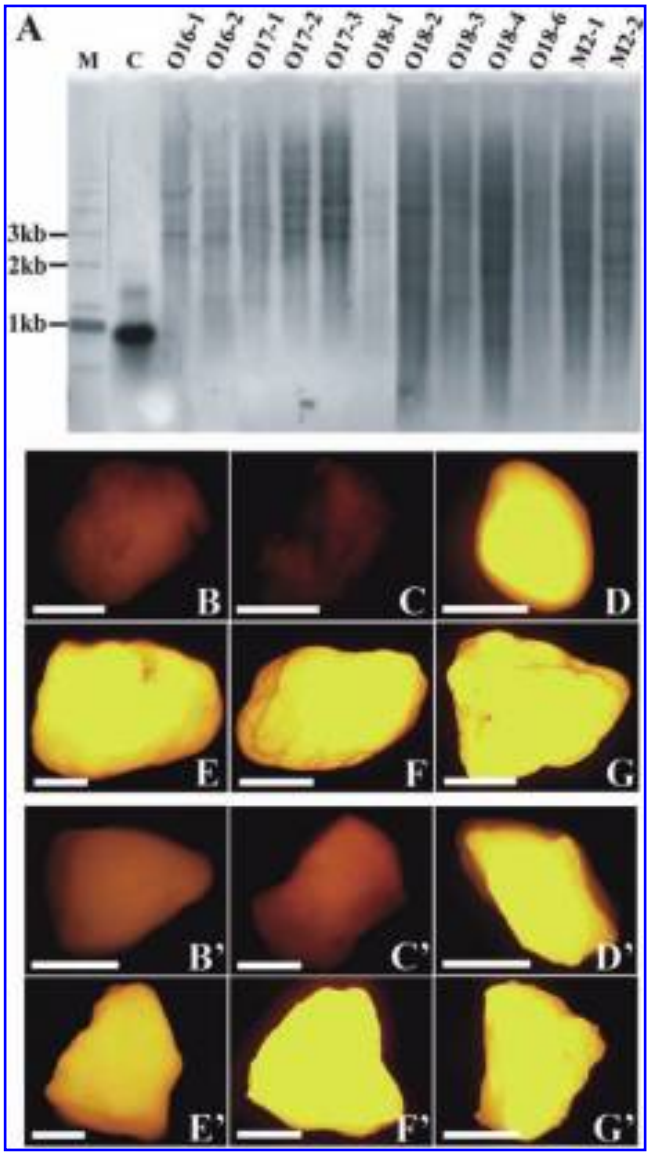

FIG. 8. Multiple provirus integration in the huKO transgenic-cloned pigs and correlation with huKO expression level. (**A**) Southern blot analysis of high molecular-weight DNA isolated from tissues of 12 offspring revealed that 2 to 17 copies of provirus were integrated into the genome of each huKO transgenic-cloned pig (lane O16-1 to lane M2-2). The molecular size marker (lane M) is 1 Kb PLUS DNA Ladder (Invitrogen). Nonlabeled probe DNA was used as a positive control (lane C). Pancreas (**B–G**) and skeletal muscle (**B′–G′**) tissue of the transgenic pigs showing a lower (pancreas: **B**,**C**, muscle: **B′**,**C′**) and higher (pancreas: **D–G**, muscle: **D′–G′**) level of huKO expression. Pictures **B**, **B′** and **C**, **C′**, respectively, correspond to O16-1 (two copies) and O18-1 (six copies), which had lower numbers of provirus integrated. Pictures **D** and **D′**, **E** and **E′**, **F** and **F′**, and **G** and **G′**, respectively, correspond to animals O16-2 (11 copies), O17-2 (10 copies), M2-1 (11–13 copies), and M2-2 (11 copies), with higher copy numbers of the integrated provirus. Scale bar = 2.5 mm (**B**,**B′**,**D**,**D′**), 5 mm (**C**,**C′**,**E–G**,**E′–G′**).

mutagenesis using PCR, while the NFAT binding site remained in the vector (Fig. 1A).

Expression was confirmed in neuronal progenitors in the huKO transgenic-cloned pigs produced in the present study. In addition, expression was also confirmed in cells such as salivary gland progenitor cells (Matsumoto et al., 2007) and pancreatic progenitor cells (data not shown). Together these suggest that the DΔNsap packaged in the VSV-G envelope maintained expression of the transgene in some types of immature cells. Further research is necessary to investigate huKO expression in various tissue stem cells and immature cells in huKO transgenic-cloned pigs.

It should be noted that the huKO cDNA was used as a fluorescent marker in the present study. Fluorescent proteins with excitation/emission spectra in the red or far-red wavelengths such as DsRed have attractive features such as low background autofluorescence (Miyawaki, 2002; Vintersten et al., 2004). In particular, there was little background autofluorescence in the liver and lung of huKO transgenic-cloned pigs, despite the fact that these organs are well known for strong autofluorescence in EGFP transgenic animals (Miyawaki, 2002; Vintersten et al., 2004).

One of the concerns with using a gene of a new fluorescent marker protein to produce transgenic pigs is toxicity of the gene product. DsRed is reported to show toxicity to cells as the result of the obligate tetramer aggregation in the perinulcear/Golgi region (Hadjantonakis et al., 2002). In contrast, huKO, which was cloned from *Fungia concinna* and humanized in the amino acid usage, dimerizes to fluoresce (Karasawa et al., 2004), being attractive feature as a fluorescent marker without apparent cytotoxicity for embryonic and/or fetal development in pigs. However, the long-term effects of huKO expression in the transgenic pigs are yet to be determined. Reproduction testing of a fully matured animal (O18-3; 17-month-old) is currently underway.

Pigs carrying fluorescent protein genes have been produced by various methods, including sperm-mediated gene transfer (Kurome et al., 2006; Webster et al., 2005; Yong et al., 2006), retroviral or lentiviral transduction of oocytes (Cabot et al., 2001), and embryos (Hofmann et al., 2003; Whitelaw et al., 2004), and SCNT using transfected donor cells (Hyun et al., 2003; Lai et al., 2002; Park et al., 2002; Watanabe et al., 2005). The SCNT approach described here allows the concurrent production of transgenic animals expressing a marker gene and nontransgenic clone-siblings from the same donor cells, which provides a useful animal model with donors and recipients of syngenic background. The importance of "translational research" including *in vivo* animal studies has been highly recognized to facilitate clinical applications of new findings in the basic sciences. The huKO transgenic-cloned pigs produced herein may have potential value as large animal models that are essential to translational research.

The present results indicate that the huKO gene can be efficiently transduced into pig fetal fibroblasts using the retroviral vector DΔNsap, and that the nuclear transfer of these cells enables efficient production of transgenic-cloned pigs that systemically express red fluorescence.

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Author Disclosure Statement

The authors declare that no competing financial interests exist.

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