Cell motion predicts human epidermal stemness

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Image-based identification of cultured stem cells and noninvasive evaluation of their proliferative capacity advance cell therapy and stem cell research. Here we demonstrate that human keratinocyte stem cells can be identified in situ by analyzing cell motion during their cultivation. Modeling experiments suggested that the clonal type of cultured human clonogenic keratinocytes can be efficiently determined by analysis of early cell movement. Image analysis experiments demonstrated that keratinocyte stem cells indeed display a unique rotational movement that can be identified as early as the two-cell stage colony. We also demonstrate that α6 integrin is required for both rotational and collective cell motion. Our experiments provide, for the first time, strong evidence that cell motion and epidermal stemness are linked. We conclude that early identification of human keratinocyte stem cells by image analysis of cell movement is a valid parameter for quality control of cultured keratinocytes for transplantation.

Introduction

Ex vivo maintenance and expansion and subsequent transplantation of adult stem cells are indispensable for successful cell therapy of self-renewing tissues, such as the epidermis and cornea epithelium. Adult stem cells maintain their stem cell properties throughout cell culture. After transplantation, they permanently engraft, self-renew, and properly produce functional progenies, which results in long-term therapeutic success (De Luca et al., 2006; Barrandon et al., 2012). Human epidermal keratinocyte stem cells (holoclones; Barrandon and Green, 1987b) can be cultivated under suitable conditions (Rheinwald and Green, 1975), and a single holoclone can generate a progeny large enough to entirely reconstitute the epidermis of an adult human for a lifetime (Rochat et al., 1994; Mathor et al., 1996). This has enabled the autologous transplantation of cultured keratinocytes onto patients with extensive burns (Gallico et al., 1984; Pellegrini et al., 1999; Ronfard et al., 2000) and genetic disorders (Mavilio et al., 2006; De Rosa et al., 2014), and the successful application of human stem cells for regenerative medicine (De Luca et al., 2006; Green, 2008; Barrandon et al., 2012; Fuchs, 2012).

A human keratinocyte culture also contains other clonogenic keratinocytes with restricted growth capabilities (Barrandon and Green, 1987b): progenitor cells (meroclones), which can regenerate an epidermis for a short duration, and transient amplifying cells (paraclones) that cannot regenerate an epidermis at all. Holoclones are eventually converted into meroclones or paraclones during serial cultivation (Barrandon et al., 2012; Rochat et al., 2012), and the loss of holoclones hinders successful transplantation (Rama et al., 2010; Pellegrini et al., 2013). Hence, for regenerative medicine, the determination of number of holoclones in a keratinocyte culture is the best criteria to assess quality (Rama et al., 2010; Barrandon et al., 2012; Rochat et al., 2012; Pellegrini et al., 2013). However, holoclones have been discriminated from meroclones and paraclones by ex post clonal analysis (Barrandon and Green, 1987b) and expression of transcription factor p63 (Pellegrini et al., 2001). A holoclone assay takes 19 d to perform (Barrandon and Green, 1987b; Barrandon et al., 2012), and that has limited its usefulness for regenerative medicine applications.

Expression of cell surface proteins including α1, α2, α4, α6, β1, and β4 integrin subunits, transferin receptor,
Rotational speed of keratinocytes in the two-cell colony stage is associated with their proliferative capacity

Normal human epidermal keratinocytes formed two-cell colonies by a single cell division of individual cells, which were observed at day 1 after seeding. It has been reported that the number of rotating two-cell colonies of normal human keratinocytes decreases along with passages (Hata et al., 2005); however, the association between the rotational speed and clonal growth remains unknown. We first examined whether the rotational speed of two-cell colonies is associated with proliferative potential in normal human epidermal keratinocytes. Rotational motion of two-cell colonies of keratinocytes was clearly observed 1 d after cells were seeded on one fourth of the normal number of feeder cells (Fig. 1 A and Videos 1 and 2). The rotational speed of each two-cell colony was measured by time-lapse observation. After addition of feeder cells, the colony was further cultivated for 5 d. Each keratinocyte colony was traced, and the number of cells in the colonies was counted (Fig. 1 A). This analysis revealed that rotational speed of two-cell colonies of normal human keratinocytes positively correlated with proliferative capacity (Fig. 1 B and Fig. S1 A). The level of ATP-binding cassette subfamily G member 2, Delta1, melanoma chondroitin sulfate proteoglycan, and leucine-rich repeats and immunoglobulin-like domains protein 1 (Lrig1) can also be used to identify human keratinocyte stem cells (Jones and Watt, 1993; Jones et al., 1995; Li et al., 1998; Lowell et al., 2000; Legg et al., 2003; Terunuma et al., 2003; Jensen and Watt, 2006; Schlüter et al., 2011). However, none of these cell surface proteins is stem cell specific, and the number of clonogenic keratinocytes in populations enriched by cell sorting based on these cell surface markers is always smaller than that of stem cells simply selected based on size with a Pasteur pipet (up to 28%; Barrandon and Green, 1985). This does not exclude the existence of reliable cell surface markers for human keratinocyte stem cells, but indicates that the cell-sorting procedure might negatively impact the stem cells (discussed in Claudinot et al. [2005] and Barrandon et al. [2012]). Thus, selective cultivation of human keratinocyte stem cells has never been established.

Here, we dissect the motion dynamics of cultured human epidermal keratinocyte stem cells by a combination of motion analysis and physics of multiparticle systems and demonstrate that a keratinocyte stem cell colony can be identified by the analysis of cell motion, an emergent property of the stem cells.

Results

Rotational speed of keratinocytes in the two-cell colony stage is associated with their proliferative capacity

Normal human epidermal keratinocytes formed two-cell colonies by a single cell division of individual cells, which were observed at day 1 after seeding. It has been reported that the number of rotating two-cell colonies of normal human keratinocytes decreases along with passages (Hata et al., 2005); however, the association between the rotational speed and clonal growth remains unknown. We first examined whether the rotational speed of two-cell colonies is associated with proliferative potential in normal human epidermal keratinocytes. Rotational motion of two-cell colonies of keratinocytes was clearly observed 1 d after cells were seeded on one fourth of the normal number of feeder cells (Fig. 1 A and Videos 1 and 2). The rotational speed of each two-cell colony was measured by time-lapse observation. After addition of feeder cells, the colony was further cultivated for 5 d. Each keratinocyte colony was traced, and the number of cells in the colonies was counted (Fig. 1 A). This analysis revealed that rotational speed of two-cell colonies of normal human keratinocytes positively correlated with proliferative capacity (Fig. 1 B and Fig. S1 A). The level of

Figure 1. Rotational speed of two-cell colonies of keratinocytes is positively correlated with their proliferative capacity. (A, left) Motion of paired human epidermal keratinocytes. (right) Clonal growth of two-cell colonies was traced and proliferative capacity was evaluated by counting cell number in the colony after 6 d of cultivation with Hoechst 33325. Bars, 20 µm. (B) Correlation between rotational speed in the two-cell colony stage (D1) and proliferative capacity (number of cell doublings) after 6 d of cultivation. Two-cell colonies were categorized in four groups depending on rotational speed: rotation score 1 (<0.125 μ/h), rotation score 2 (≥0.125 μ/h and <0.25 μ/h), rotation score 3 (≥0.25 μ/h and <0.5 μ/h), and rotation score 4 (≥0.5 μ/h). The data shown (n = 126 colonies) were obtained from nine independent experiments. P-value was calculated by Mann-Whitney nonparametric U test. Full set of data is shown in Fig. S1 A. (C) Rotational motion and expression of IVL in two-cell colonies of keratinocytes. IVL expression was categorized in three groups depending on the number of IVL-expressing cells: IVL score 0, no cells; IVL score 1, single cell; and IVL score 2, two cells. Bar, 20 µm. (D) Frequency of two-cell colonies of keratinocytes with each rotation and IVL scores. The data shown (n = 63 colonies) were obtained from triplicate experiments. P-value was calculated by Mann-Whitney nonparametric U test.
involution (IVL) expression is also related to proliferative capacity of keratinocytes (Watt and Green, 1981; Barrandon and Green, 1985). We further found that faster rotating two-cell colonies did not express IVL, whereas the colonies expressing IVL in one or both keratinocytes rarely rotated (Fig. 1, C and D). These data indicate that the keratinocytes with the ability to rotate around the neighbor in the two-cell colony stage also had the ability to proliferate and make a large colony by clonal growth. Therefore, the correlation between rotational speed in the two-cell colony and its clonal growth could not be examined. In high density inoculation, however, keratinocytes formed two-cell colonies and some of them exhibited a rotational motion (Videos 3–5), as reported previously (Hata et al., 2005). This indicates that keratinocytes rotate around the neighboring cells when two cells are in contact with each other, even if maintained in serum-free media.

**Rotational motion gives rise to collective dynamics, which predicts epidermal stemness**

Clonogenic keratinocytes form progressively growing colonies (Barrandon and Green, 1987a,b; Nanba et al., 2013b) that contain more than a hundred cells with differing proliferative capacities (Barrandon and Green, 1987b). In progressive growing colonies, individual keratinocytes spontaneously moved with different locomotion speeds (Fig. 2 A; Fig. S2, A and B; and Video 3); cells located at the inner portion of the colony rotate CCW. Each color indicates different locomotion speeds. The data shown were obtained from a single representative experiment using a random number generator with three random seeds (triplicate experiments). The colony containing 20% of CCW cells showed the highest mean speed of locomotion even if all cells had the same rotational speed (0.5 μ/h). (middle) Rotation speed of cells determined cell locomotion speed in the colony. The percentage of CCW rotating cells was fixed at 20%. (right) Variation of locomotion speeds of cells was reproduced with a mixture of fast (0.5 μ/h) and slow (0.2 μ/h) rotating cells. The percentage of CCW rotating cells was fixed at 20%. The data shown were obtained from a single representative experiment using a random number generator with three random seeds (triplicate experiments). (F) Schematic representation of cell locomotion speed in each clonal type. The simulation predicted that a holoclone colony could be identified by measuring cell locomotion speed.
that of a progressively growing colony in culture (Fig. 2, A, B, and D). The colonies containing 20% of CCW rotating cells showed the maximum mean speed of cell locomotion (Fig. 2 E). Locomotion speed of cells in the colony was completely dependent on rotational speed of cells (Fig. 2 E). Various mixtures of fast (0.5 \( \pi \) h) and slow (0.2 \( \pi \) h) rotating cells in the colony gave rise to variations in the mean locomotion speed of cells in the colony (Fig. 2 E). This scenario revealed the possibility of predicting a keratinocyte stem cell colony by measuring cell locomotion speed, if rotational speed of keratinocytes was indeed associated with their proliferative capacity (Fig. 2 F).

Keratinocyte stem cell colonies can be identified by measuring cell locomotion speed. To validate this prediction, we measured cell locomotion speed in each growing colony by time-lapse observation in 7 d of culture, and then assessed proliferative capacity by clonal analysis (Barrandon and Green, 1987b; Fig. 3, A and B). The mean speed of cell locomotion in the colony at day 7 was \( \approx 25–40 \mu \text{m/h} \) (Fig. 2 D). However, appearance of counterclockwise (CCW) rotating cells generated motion dynamics in the cells located at the inner portion of the colony, and distribution of locomotion speed was almost identical to that of a progressively growing colony in culture (Fig. 2, A, B, and D). The colonies containing 20% of CCW rotating cells showed the maximum mean speed of cell locomotion (Fig. 2 E). Locomotion speed of cells in the colony was completely dependent on rotational speed of cells (Fig. 2 E). Various mixtures of fast (0.5 \( \pi \) h) and slow (0.2 \( \pi \) h) rotating cells in the colony gave rise to variations in the mean locomotion speed of cells in the colony (Fig. 2 E). This scenario revealed the possibility of predicting a keratinocyte stem cell colony by measuring cell locomotion speed, if rotational speed of keratinocytes was indeed associated with their proliferative capacity (Fig. 2 F).
A variation in integrin α6 subunit expression in individual keratinocytes was observed (Fig. 4 A); keratinocytes with higher α6 integrin expression moved faster than those with lower expression (Fig. 4 B). The level of α6 integrin expression in human keratinocytes is correlated with their proliferative capacity (Li et al., 1998) and clonal types (Fortunel et al., 2010). We next fractionated keratinocytes in progressively growing colonies into α6 integrin high- and low-expressing populations (α6high and α6low). The culture of keratinocytes on a feeder layer of 3T3 cells also contains terminal colonies that have an irregular shape and is mostly composed of large and flattened basal cells (Nanba et al., 2013b). Cellular fractions mainly containing keratinocytes derived from such colonies were identified and discriminated from keratinocytes comprising growing colonies by IVL expression and flow cytometric signatures of each subfraction (Fig. S3). We then found that α6high but not α6low keratinocytes in the progressively growing colony maintained proliferative capacity through serial cultivation (Fig. 4 C). Flow cytometric analysis also revealed that α6high keratinocyte population contained the smallest cells (Fig. S3 D), which possess higher clonogenic ability (Barrandon and Green, 1985). Collectively, these data indicate that keratinocytes with higher expression of α6 integrin in growing colonies possessed both higher locomotive and proliferative capacities.

The expression level of α6 integrin is associated with locomotion speed and proliferative capacity

In a progressively growing colony, a variation in integrin α6 subunit expression in individual keratinocytes was observed (Fig. 4 A); keratinocytes with higher α6 integrin expression moved faster than those with lower expression (Fig. 4 B). The level of α6 integrin expression in human keratinocytes is correlated with their proliferative capacity (Li et al., 1998) and clonal types (Fortunel et al., 2010). We next fractionated keratinocytes in progressively growing colonies into α6 integrin high- and low-expressing populations (α6high and α6low). The culture of keratinocytes on a feeder layer of 3T3 cells also contains terminal colonies that have an irregular shape and is mostly composed of large and flattened basal cells (Nanba et al., 2013b). Cellular fractions mainly containing keratinocytes derived from such colonies were identified and discriminated from keratinocytes comprising growing colonies by IVL expression and flow cytometric signatures of each subfraction (Fig. S3). We then found that α6high but not α6low keratinocytes in the progressively growing colony maintained proliferative capacity through serial cultivation (Fig. 4 C). Flow cytometric analysis also revealed that α6high keratinocyte population contained the smallest cells (Fig. S3 D), which possess higher clonogenic ability (Barrandon and Green, 1985). Collectively, these data indicate that keratinocytes with higher expression of α6 integrin in growing colonies possessed both higher locomotive and proliferative capacities.

α6 integrin is required for rotational and collective motion

α6 integrin was also expressed in rotating two-cell colonies of normal human epidermal keratinocytes (Fig. 5 A). We next examined whether α6 integrin is involved in the rotational motion of two-cell colonies of keratinocytes by using a doxycyclin-inducible α6 integrin gene (ITGA6)–specific knockdown system (Matsushita et al., 2013; Nanba et al., 2013b). shRNA-expressing cells were easily traced as GFP-positive (GFP+) cells, and a lentivirus carrying shRNA targeted to ITGA6 efficiently decreased α6 expression in human epidermal keratinocytes (Fig. S4, A–D). Rotational speed was significantly decreased...
in ITGA6, but not control shRNA-transduced two-cell colonies (Fig. 5 B). We further found that locomotion speed of GFP+ cell populations in progressive growing colonies was significantly slower than that of GFP-negative (GFP−) cell populations in colonies infected with a lentivirus carrying shRNA targeted to ITGA6, but not the control shRNA (Fig. 5, C and D). These results indicate that α6 integrin was required for rotational and collective motion of human keratinocytes. Altogether, we revealed that keratinocytes expressing higher amounts of α6 integrin, which is required for rotational motion of keratinocytes, also possessed higher proliferative capacity, which corroborates that the rotational speed of keratinocytes was correlated with their proliferative capacity, as shown in Fig. 1.

α6β4 integrin is required for collective motion

α6 integrin forms a heterodimer with β4 subunit and functions as a surface receptor for laminin-332 (Margadant et al., 2008). We confirmed the polarized expression of α6β4 integrin (Marchisio et al., 1991) at the basal surface of keratinocytes (Fig. 6, A and B). α6β4 integrin can be linked with cytokeratins via cytoplasmic proteins, and cytoskeleton-linked α6β4 integrin is detergent insoluble and can be detected even if cells are treated with detergent before fixation (Rabinovitz et al., 1999). In cultured human epidermal keratinocytes, α6β4 integrin was also detectable when treated with 0.5% Triton X-100 before fixation (Fig. 6 C). Basal, but not lateral, distribution of α6β4 integrin was more evident by Triton X-100 pretreatment (Fig. 6 C). However, electron microscopy demonstrated that hemidesmosomes, which appear as electron-dense cytoplasmic plaques at the basal surface of cells, were only detected in the terminal colony but hardly observed in the progressively growing colony (Fig. 6 D). We further examined whether α6β4 integrin is involved in keratinocyte locomotion. Because of the limited access of inhibitory antibodies to the basal surface of cells in the colony, we investigated keratinocyte movements in two-dimensional cell aggregates, which were formed after high density keratinocyte inoculation (Fig. S5 and Materials and methods). Locomotion speed of keratinocytes incubated with anti-α6 (GoH3) and β4 integrin (ASC-8) antibodies in two-dimensional aggregates significantly decreased, whereas it was not affected by normal rat and mouse IgG (Fig. 6 E). These data indicate that α6β4 integrin was not organized into anchoring complexes of hemidesmosomes in growing colonies, but was associated with cytokeratins and involved in collective motion of keratinocytes by mediating functional adhesion to extracellular substrates in the progressively growing colony.

Discussion

The proliferative capacity of human epidermal keratinocyte stem cells has been well studied. In contrast, their locomotive capacity has not been well investigated because stem cells are assumed to be anchored in their niche. Our present work has four major findings concerning the motion of human keratinocyte stem cells. First, keratinocytes with higher proliferative capacity show a rotational motion in two-cell stage colonies. Second, the rotational motion of keratinocyte stem cells triggers collective motion of the cells within the colony. Third, collective motion analysis identifies keratinocyte stem cell colonies. Fourth, α6 integrin is involved in rotational and collective motion of keratinocytes.

The mechanism of rotational motion of the two-cell colony of keratinocytes and how it is associated with growth capacity is still unclear. We have previously reported that single keratinocytes can create helical tunnels in fibrin matrix (Ronfard and Barrandon, 2001), which might be related with the rotational motion. Mammary epithelial cells also exhibit rotational motion (Kino-oka et al., 2004), which is required for sphere formation in three-dimensional culture (Tanner et al., 2012). In mammalian epidermis, keratinocyte stem cells are located in the basal layer of the interfollicular epidermis and epidermal appendages (Rochat et al., 1994; Jones...
and Wilgram, 1973; Cavani et al., 1993). Although directed migration is indispensable for wound closure, collective motion generated by keratinocyte stem cells might also be involved in epidermal wound healing.

Image-based identification of cultured stem cells and evaluation of their potency are required for quality assurance of stem cell culture in regenerative medicine (Ker et al., 2011) and also for high-throughput screening in stem cell research (Erdmann et al., 2012). Recent studies have established noninvasive and morphology-based evaluation methods to identify mesenchymal stem/progenitor cell potency (Kino-oka et al., 2009; Seiler et al., 2012; Matsuoka et al., 2013). Maintenance and self-renewal of keratinocyte stem cells in culture are definitely associated with successful transplantation for epidermal regeneration. For regenerative medicine, the determination of number of holoclones in a keratinocyte culture is the best criteria to assess quality (Rama et al., 2010; Barrandon et al., 2012; Rochat et al., 2012; Pellegrini et al., 2013). However, a holoclone assay takes 19 d to perform (Barrandon and Green, 1987b; Barrandon et al., 2012), and that has limited its usefulness for regenerative medicine applications. Image-based
noninvasive identification of cultured human keratinocyte stem cells enables us to monitor and validate their successful cultivation in situ, which is essential for engraftment of transplanted cells and the long-term maintenance of the regenerated epidermis and cornea epithelium in the patients (Gallico et al., 1984; Pellegrini et al., 1997, 1999; Ronfard et al., 2000; Rama et al., 2001; Rama et al., 2010). This technology is also available for selection of normal and genetically modified keratinocyte stem cells in cultured keratinocytes derived from the patient’s skin (Mavilio et al., 2006) or differentiated from embryonic stem cells and patient-specific induced pluripotent stem cells for therapy (Green et al., 2003; Metallo et al., 2008; Guenou et al., 2009; Itoh et al., 2011).

Our findings are the basis of a noninvasive method that relies on the analysis of cell motion to estimate the growth capacity of keratinocytes in culture and monitor and validate the quality of these cells for transplantation. In practice, the combination of time-lapse observation of keratinocyte cultures and an image processing technology that can recognize and trace individual cells within the densely packed colonies can achieve in situ identification of keratinocyte stem cells through the automatic measurement of cell locomotion speed. This enables us to monitor whether the culture contains enough keratinocyte stem cells with higher locomotive capacity and eliminate the cultures that are not suitable for transplantation before making confluent keratinocyte sheets. Selective cultivation of keratinocyte stem cells can also be achieved in combination with automated aspiration of stem cell colonies from the feeder cell layer (Schneider et al., 2008). Advances in our simulation based on physics of multiparticle systems, by including the cell division and the growth of a colony, will also contribute to profound understanding of collective dynamics of keratinocyte stem cells during keratinocyte sheet formation. Although further investigations and technological developments are still required, phase-contrast time-lapse imaging with an image processing algorithm will definitely improve the clinical outcome of cell therapy and the efficiency of cell manufacturing for regenerative medicine.

Materials and methods

Cell culture
Normal human epidermal keratinocytes were isolated from neonatal skin. Frozen keratinocytes were thawed and cultivated at clonal density on a feeder layer of irradiated or mitomycin C–treated 3T3-J2 cells, at 37°C and 10% CO2 in a 1:3 mixture of the DMEM and Ham’s F12 medium supplemented with 10% FCS, 5 µg/ml insulin, 0.4 µg/ml hydrocortisone, 10^{-5} M cholera toxin, and 2 × 10^{-9} M triiodothyronine, as described previously (Rheinwald and Green, 1975; Rochat et al., 1994). Human epidermal keratinocytes were also cultivated with CnT-PR medium (CELLnTEC), EpiLife medium containing supplement S7 (Life Technologies), and MCD8153 medium containing bovine pituitary extract (Hashimoto et al., 1994). Keratinocytes were used between passages 2 and 7. The medium was changed every 4 d. Cultures were fixed with 3.7% buffered formaldehyde and stained with 1% rhodamine B and keratinocyte colonies were counted under a binocular microscope (SMZ265; Nikon). Clonal analysis was performed as described previously (Barrandon and Green, 1987b). In brief, human keratinocytes were cultivated at clonal density on a feeder layer of irradiated or mitomycin C–treated 3T3-J2 cells. Well-isolated colonies were then individually trypsinized in a cloning ring and subcultured into a 10-cm cell culture dish so clonal types could be evaluated.

Time-lapse imaging and image processing
Human epidermal keratinocytes were seeded at clonal density in a 35-mm cell culture dish (Corning) with irradiated or mitomycin C–treated 3T3-J2 cells and grown for 6 or 7 d without EGF. For time-lapse imaging, cells were maintained at 37°C and 10% CO2 in a chamber mounted on a microscope (Axiovert 200M; Carl Zeiss). Images were obtained at 5-min intervals, for 30, 60, and 180 min, depending on experimental conditions, with an AxioCam camera (AxioCamHR2; Carl Zeiss) using Enhanced Contrast Plan Neofluar 5x/0.16 and 10x/0.30 and LD A-Plan 20x/0.30 objective lenses. Time-lapse images were acquired with AxioVision (Carl Zeiss) and analyzed with MetaMorph (Molecular Devices) or Velocity (PerkinElmer) on the graphic tablet (Wacom). The angle of contact surface between cells in a two-cell colony was given by the top right angle of contact surface against the perpendicular axis. The rotational speed of a two-cell colony was assessed as the amount of change in the angle of the colony.

Immunofluorescence microscopy
Keratinocytes were seeded at clonal density in a 35-mm cell culture dish with irradiated or mitomycin C–treated 3T3-J2 cells and grown for 6 d. The cells were fixed in 4% PFA in PBS at 4°C for 10 min, and subsequently treated with 0.5% Triton X-100 in PBS for 10 min. In the detergent-insoluble experiment, the cells were treated with 0.5% Triton X-100 in PBS for 10 min before fixation. After the treatment with 1% BSA, the cells were incubated with primary antibodies for 1 h at RT or overnight at 4°C, washed in PBS, and subsequently incubated with FITC- and Cy3-conjugated secondary antibodies (Jackson Immunoresearch Laboratories, Inc.) for 1 h at RT. After a wash with PBS, cells were incubated with Hoechst 33258 (Molecular Probes), mounted with a fluorescent mounting medium (Dako), and examined with a microscope (Axiovert 200M; Carl Zeiss) with a Plan Apochromat 20x/0.8 objective lens (Carl Zeiss). Confocal imaging was performed with an A1 confocal microscope (Nikon) with Plan Apochromat 20x/0.75 and 40x/0.95 lenses (Nikon), and images were obtained and analyzed with NIS-Elements (Nikon). Primary antibodies used for immunofluorescence microscopy were as follows: a mouse monoclonal antibody against α6 integrin (clone 17D11; gift from Y. Hiroko, Nagoya University, Nagoya, Japan), a rat monoclonal antibody against α6 integrin (clone GoH3; BD), a mouse monoclonal antibody against β4 integrin (clone 3E11; EMD Millipore), and a mouse monoclonal antibody against IVL (clone SYS; Abcam). The mouse monoclonal antibody against α6 integrin (clone 17D11) was produced by using the extracellular domain of bovine α6 integrin as the antigen.

Flow cytometry and cell sorting
Trypsinized and resuspended keratinocytes were incubated with a FITC-conjugated rat monoclonal antibody against α6 integrin (GoH3; BD) for 1 h on ice. After three washes with HBSS (+), the cells were resuspended in culture medium, sorted using the FACSaria cell sorter (BD), and collected into culture medium. For IVL experiments, trypsinized and resuspended keratinocytes were incubated with mouse monoclonal antibody against IVL (SIM; Abcam) for 1 h on ice. Keratinocytes were then incubated with phycoerythrin-conjugated goat polyclonal antibody against mouse IgG (Santa Cruz Biotechnology, Inc.) for 1 h on ice. After three washes with HBSS (+), the cells were then resuspended in HBSS (+) and analyzed by using the FACSCan flow cytometer (BD).

Plasmid construction and preparation of lentivirus vectors
A doxycyclin-inducible gene-specific knockdown system using a lentivirus was described previously (Matsushita et al., 2013; Namba et al., 2013b). The HIV-based self-inactivating lentiviral expression vector plasmid CS-CA-MCS was provided by the Institute of Physical and Chemical Research BioResource Center, Japan. Three plasmids, pTet-On-Advanced vector, pTRE-Tight vector (Takara Bio Inc.), and pcDNA 6.2-GW/EmGFP-miR vector (Invitrogen), were obtained, and their components were used to construct a transgene cassette consisting of two expression units for inducible gene knockdown. The cDNA fragment of reverse Tet-controlled transactivator was recovered from the pTet-On-Advanced vector and ligated into the pRES vector (Takara Bio Inc.), upstream of the internal ribosome entry site (IRES) sequence. The blasticidin-resistance gene (Bsd) was ligated into this plasmid, downstream of the IRES sequence, resulting in the generation of pTet-On-IRES-Bsd, containing one transgene unit. In contrast, the Drai–PvuII fragment of the pcDNA 6.2-GW/EmGFP-miR vector containing EmGFP cDNA and pre-miRNA sequence was recovered and inserted into the pTRE-Tight vector, downstream of the Tet-responsive promoter. This resulted in the vector pTRE-EmGFP-miR, which contained another transgene unit. Finally, the fragment of the nTA-IRES-Bsd was inserted into the lentivirus expression vector plasmid CS-CA-MCS, directly
downstream of the CAG promoter sequence, and then another unit, the TRE-EmGFp-miR fragment, was inserted into the resulting plasmid between the Bsd and WPRE sequence. The TRE-EmGFp-miR unit was arranged in the opposite direction as the CAG-driven rTa-IRES-Bsd unit, yielding a new single lentivirus expression plasmid for inducible gene silencing, CS-CaT-ITGA6-Bsd-TRE-EmGFp-miR (Fig. S4 A). To construct the lentivirus vector for inducible silencing of the human integrin α6 (ITGA6) gene expression, two synthetic oligonucleotides designed by BLOCK-TiTm RNAi technologies were obtained (Life Technologies). The sequences were 5′-TGCTGAAATGCTGAGGTACGGC-3′ and 5′-CTGTGTTGAGCCTGGACGCAGTGG-3′ for Hmi40869_bot_ITGA6 and 5′-TGCTGAAATGCTGAGGTACGGC-3′ and 5′-CTGTGTTGAGCCTGGACGCAGTGG-3′ for Hmi40869_bot_ITGA6. The double-stranded DNA was inserted between the 5′-mirt and 3′-mirt flanking sequences of the vector plasmid. The shRNA-negative control sequence presented by Life Technologies was used to construct a negative control vector. The sequences used as negative controls were 5′-TGCTGAAATGCTGAGGTACGGC-3′ and 5′-CTGTGTTGAGCCTGGACGCAGTGG-3′ for Hmi40869_bot_ITGA6 and 5′-TGCTGAAATGCTGAGGTACGGC-3′ and 5′-CTGTGTTGAGCCTGGACGCAGTGG-3′ for Hmi40869_bot_ITGA6. Using these ITGA6-inducible knockdown plasmids, lentiviral particles were prepared by standard transfection procedures and used to introduce the transgene into 2 × 10^5 cells. After transduction of the transgenes at a multiplicity of infection of 1 as previously described (Nanba et al., 2013a), the cells were treated with 100 nM doxycycline to induce silencing of the ITGA6 gene and subsequently analyzed.

Electron microscopy
A keratinocyte culture containing growing and terminal colonies was fixed in 0.1 M cacodylate buffer, pH 7.3, containing 2.5% glutaraldehyde and 2% PFA, and was then immersed in 1% osmium tetraoxide in the same buffer. Dehydration in a gradient series of ethanol was followed by embedding in PolyBed 812 (Polysciences). Ultrathin sections were cut on a Reichert ultramicrotome (Leica), stained with uranyl acetate and lead citrate, and observed with an electron microscope (1200EX; JEOL).

Two-dimensional keratinocyte aggregation assay
Resuspended keratinocytes were incubated with 20 µg/ml of an inhibitory antibody against α6 (clone GoH3; BD) or β4 integrin (clone ASC-8; EMD Millipore) for 1 h on ice. Cells were then washed with HBSS (±) (Invitrogen) twice, and 5.0 × 10^4 cells were seeded into a 35-mm cell culture dish (Corning). A cell monolayer was irradiated, or a monolayer C-treated 3T3-J2 cells. Keratinocytes formed two-dimensional cell aggregates during overnight culture. The aggregates were maintained at 37°C and 10% CO2 in a chamber mounted on a microscope (Axiovert 200M; Carl Zeiss), and then serial images of the aggregates were obtained at 5-min intervals for 30 min. Locomotion speed was measured by analyzing time-lapse images with Volocity (Perkin-Elmer) on the graphic tablet.

Computer simulation
We defined the rotational motion of a target cell as the rotation of surrounding cells around the target cell. The rotational speed of surrounding cells was set to decrease in function of the distance / from the target cell. All cells in a colony were provided with the ability to rotate at π/2 per hour per cell for the two-cell colony. This arrangement of rotation for each cell results in each one of the two cells rotating at πh around the center of two cells. We set the functional form of the rotational speed in an exponential form as \( \omega = \omega_0 \exp(-|l_0|/d) \), where \( l_0 \) is the equilibrium distance between contacting cells and \( \omega_0 \) and \( \alpha \) are parameters to be fixed by comparison with observations. The \( \omega_0 \) has to be smaller, as the number of stiffer cells increases with the total number \( N \) of cells in a colony. To avoid the overlap of cells, we introduced a process where overlapping cells repel each other and go back to the equilibrium distance by the same amount for the overlapping cells. We made this procedure to all cells in a colony with a time step of 1 min. To avoid the outward motion of cells away from a colony, we introduced a boundary with a circle of radius \( R \) from the center of the colony. When a cell tried to move out from the cell boundary, the cell was pushed back. With this setup, we made a Fortran program to simulate the movement of cells in a colony with various numbers of cells. For the simulation, we took all cells as spheres with the radius of \( r_{avg} = 10 \) µm, and also provided the variable extension of \( e = 2 \) µm. Hence, the equilibrium distance of contacting cells was assumed as \( l_0 = 24 \) µm. For the presentation of numerical results, we took \( \omega_0 = \pi/2 \) for \( n = 2 \) and gradually decrease to \( \pi/5 \) for \( n = 100 \) with \( d = l_0/2 \), to take into account the effect of sticking of cells controlled by the distance parameter \( d \). We defined the radius of the boundary of a colony as \( R^2 = (l_0^2/2N) \). All cells were distributed randomly in the colony by using the random number generator. When we introduced cells with opposite or reduced rotational speed by some fraction, we also used the random number generator to confer these parameters to the cells. The Fortran program is provided in the online supplemental material.

Online supplemental material
Fig. S1 shows motion dynamics of keratinocytes seeded at clonal density in various cell culture media. Fig. S2 shows collective motion dynamics of keratinocytes in a progressively growing colony. Fig. S3 shows fractionation of cultured keratinocytes based on α6 integrin and β1 expression. Fig. S4 shows characterization and validation of functional shRNA targeted to ITGA6. Fig. S5 shows that ITGA6 integrin is involved in collective motion of keratinocytes. Videos 1 and 2 show the dynamics of two-cell colonies, as shown in Fig. 1 A. Videos 3–5 show motion dynamics of keratinocytes at high density culture in serum-free media Cn1t-FR, Epilife, and MCD1535, respectively. Video 6 shows collective motion dynamics of keratinocytes in a progressively growing colony, as shown in Fig. S2. The supplemental program file contains the Fortran program that we used for the simulation experiments. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.201409024/DC1. Additional data are available in the JCB DataViewer at http://dx.doi.org/10.1083/jcb.201409024.dv.

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