Dynamic equilibrium between cancer stem cells and non-stem cancer cells in human SW620 and MCF-7 cancer cell populations

Tissue-specific stem cells exist in many adult tissues and can be identified and isolated using specific antigen profiles. Many, if not all, tumours and established tumour cell lines contain cancer stem cells (CSCs) isolated via cell-surface markers (Dalerba et al, 2007; Visvader and Lindeman, 2008). Cancer stem cell populations were assessed over multiple generations under normal and irradiation surroundings. Supplement and inhibition of TGF-β1, as well as immunofluorescence assay of E-cadherin and Vimentin, were performed. Surface antigen markers of CSCs and NSCCs exist in an intrinsic homoeostasis state with spontaneous and in situ visualisable inter-conversions, irrespective of prior radiations. Supplement with TGF-β1 accelerates the equilibrium, whereas inhibition of TGF-β signalling disturbs the equilibrium and significantly decreases CSC proportion. Epithelial mesenchymal transition (EMT) might be activated during the process.

BACKGROUND: Cancer stem cells (CSCs) paradigm suggests that CSCs might have important clinical implications in cancer therapy. Previously, we reported that accumulation efficiency of CSCs is different post low- and high-LET irradiation in 48 h.

METHODS: Cancer stem cells and non-stem cancer cells (NSCCs) were sorted and functionally identified through a variety of assays such as antigen profiles and sphere formation. Inter-conversion between CSCs and NSCCs were in situ visualised. Cancer stem cells proportions were assayed over multiple generations under normal and irradiation surroundings. Supplement and inhibition of TGF-β1, as well as immunofluorescence assay of E-cadherin and Vimentin, were performed.

RESULTS: Surface antigen markers of CSCs and NSCCs exist in an intrinsic homoeostasis state with spontaneous and in situ visualisable inter-conversions, irrespective of prior radiations. Supplement with TGF-β1 accelerates the equilibrium, whereas inhibition of TGF-β signalling disturbs the equilibrium and significantly decreases CSC proportion. Epithelial mesenchymal transition (EMT) might be activated during the process.

CONCLUSION: Our results indicate that the intrinsic inter-conversion and dynamic equilibrium between CSCs and NSCCs exist under normal and irradiation surroundings, and TGF-β might have important roles in the equilibrium through activating EMT. A large number of studies have reported that CSCs can be spontaneously generated from NSCCs (Meyer et al, 2009; Chaffer et al, 2011) and more interestingly, can be induced from NSCCs with either chemical treatment (Achuthan et al, 2011; Iliopoulos et al, 2011) or ionising irradiation (Liang et al, 2010). Previously, we also reported that accumulation efficiency of CSCs is quite different post low- and high-LET irradiation in 48 h (Quan et al, 2011). The relationships between CSCs and NSCCs have received enormous attention but remain controversial. In addition, the proportion of CSCs remains constant over multiple generations in many established cancer cell lines (Iliopoulos et al, 2011), but the basis of this phenomenon is poorly understood.

To address these questions, CSCs and NSCCs from SW620 colon cancer and MCF-7 breast cancer cells were separated through CD133, CD44, and CD24 cell-surface antigen markers, respectively. The results showed that surface antigen markers of CSCs and NSCCs exist in an intrinsic homoeostasis state with spontaneous and in situ visualisable inter-conversions, irrespective of prior radiations. Supplement with TGF-β1 accelerates the equilibrium, whereas inhibition of TGF-β signalling disturbs the equilibrium and significantly decreases CSCs proportion. Further, immunofluorescence studies with E-cadherin and Vimentin, markers of epithelial mesen-
chymal transition (EMT), suggested that EMT might be activated during the process. Our results suggest a possible reason for retaining a constant CSC proportion of many established tumour cell lines.

MATERIALS AND METHODS

Cell culture

Human colon cancer SW620 cells and breast cancer MCF-7 cells were purchased from America Type Culture Collection. They were cultured in Dulbecco’s modified Eagle’s medium supplemented with 10% foetal bovine serum, 100 U ml$^{-1}$ penicillin, and 100 µg ml$^{-1}$ streptomycin at 37 °C in 5% CO$_2$. For some experiments, cells were cultured with or without 0.4 ng ml$^{-1}$ TGF-β1 (Perprotech, Rocky Hill, NJ, USA) or 1 µM SB431542 (Sigma, St Louis, MO, USA).

Cell staining and flow cytometry

Matched subpopulations were separated as described (Al-Hajj et al., 2003; O’Brien et al., 2007; Ricci-Vitiani et al., 2007). In brief, cells were stained at a concentration of 10$^5$ cells per 100 µl of buffer. Anti-CD133/1(AC133)-APC, anti-CD133/1(AC133)-PE (Miltenyi Biotec, Auburn, CA, USA), anti-CD44-PE (BD Pharmingen, San Jose, CA, USA), and anti-CD24-Alex488 (BioLegend, San Diego, CA, USA) antibodies were used for flow cytometric sorting/assay of SW620 and MCF-7 cells, respectively. For all experiments, samples were sorted on a BD FACS Diva Software (BD Bioscience, San Jose, CA, USA), anti-CD44-PE (BD Pharmingen, San Jose, CA, USA) and anti-CD24-Alex488 (BioLegend, San Diego, CA, USA) antibodies were used for flow cytometric sorting/assay of SW620 and MCF-7 cells, respectively. For all experiments, samples were sorted on a BD FACS Aria II and analysed on a BD LSR II flow cytometer using BD FACS Diva Software (BD Bioscience, San Jose, CA, USA). Side scatter and forward scatter profiles were used to eliminate debris and cell doublets.

Irradiation protocol

Cells were irradiated at room temperature with $^{60}$Co γ-ray at a dose rate of 1 Gy min$^{-1}$ for the time required to generate a dose curve of 0, 2, 4, and 6 Gy. Fraction irradiations were performed as 2 Gy per time for two times with 2 days interval (2 Gy × 3). Corresponding controls were sham irradiated.

Mammosphere formation assay

Sphere formation assays were performed as described previously (Phillips et al., 2006).

Phosphorylated H2AX staining

Gamma-H2AX assays were performed as described previously (Muslimovic et al., 2008; Diehn et al., 2009).

In vitro colony formation assay

Colonies formation assays were performed immediately after irradiation by plating cells into triplicate six-wells plates as described previously (Phillips et al., 2006).

In situ immunofluorescence

The chips were made as we described previously (Luo et al., 2008) with minor revision. In brief, purified NSCCs and CSCs were stained with the mouse monoclonal antibody against human CD133 antigen coupled with R-phycocerythrin (CD133/1(AC133)-PE from Miltenyi Biotec) together with the DNA-binding dye Hoechst 33342 (Invitrogen, Carlsbad, CA, USA) for 25 min in dark at 4 °C, washed twice, and reloaded in medium at a density of 5 × 10$^3$ cells ml$^{-1}$, respectively. After degassing the chip, 25 µl mixtures were pipetted into the reservoir that has a total volume of about 40 µl. The cell suspension was aspirated into the cell culture rooms because of the negative pressure created by gas reabsorption of the degassed polydimethylsiloxane (PDMS). After loading of the sample, the cells in the reservoir were removed and 35 µl of medium was added and cultured normally. After 2 h incubation, cells were photographed for the first time as described below. For immunofluorescence staining of cells at defined time points such as 12 h or 24 h, media in reservoir was removed and 20 µl medium with appropriate concentration of CD133/1(AC133)-PE (Miltenyi Biotec) was added, and then incubated in dark at 37 °C and 5% CO$_2$ for 1 h to ensure the adequate solution change and staining processing by convective and diffusive mass transport (diffusion time scale is about half-an-hour). After incubation, the medium with CD133/1(AC133)-PE in reservoir was removed and 35 µl fresh medium was added and incubated in dark at 37 °C and 5% CO$_2$ for 30 min for washing the cells. Cells were washed twice and were immediately photographed as described below.

At defined time points such as 12 h or 24 h after cell loading, each cell culture room was captured automatically by EMCCD (Andor iXon X3, Belfast, Northern Ireland) with one DIC channel and two fluorescent channels (Hoechst 33342 for nuclei, DAPI; PE for CD133, TRITC) under × 20 objective lens (Nikon Ti-E, Tokyo, Japan). Exposure time for each channel was 20 ms. On the average, it took about 3 min to record all the cell culture rooms in a chip.

Statistical analysis

All data are pooled from at least three independent experiments and the results are presented as means ± s.d. Significance between two groups were assessed using Student’s t-test. A P-value of <0.05 between groups was considered significant.

RESULTS

Enrichment of the CSCs and NSCCs

Purified CSCs and NSCCs from human SW620 colon cancer and MCF-7 breast cancer cells were isolated using fluorescence-activated cell sorting (FACS). For SW620 cells, CSCs and NSCCs were enriched via CD133 cell-surface antigen marker (Figures 1A–C) as previously reported (O’Brien et al., 2007; Ricci-Vitiani et al., 2007). The enrichment of CSCs and NSCCs is efficient, as shown in Figures 1B and C. For MCF-7 cells, CSCs and NSCCs were separated using CD44 and CD24 cell-surface antigen markers (Al-Hajj et al., 2003) (Supplementary Figure S1A).

Functional verification of the CSCs and NSCCs

In accordance with the phenotypic definition and presence of surface antigen markers in CSCs, the CD133$^+$ and CD44$^-$CD24$^-$ enriched CSCs are capable of forming self-renewing spheres efficiently (Figures 1D–F and Supplementary Figure S1B). In brief, cells were loaded into the chip and incubated at 37 °C and 5% CO$_2$ for 1 h to ensure the adequate solution change and staining processing by convective and diffusive mass transport (diffusion time scale is about half-an-hour). After incubation, the medium with CD133/1(AC133)-PE in reservoir was removed and 35 µl fresh medium was added and incubated in dark at 37 °C and 5% CO$_2$ for 30 min for washing the cells. Cells were washed twice and were immediately photographed as described below.

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In situ visualisation of the inter-conversion between CSCs and NSCCs

To clarify kinetics of the inter-conversion between NSCCs and CSCs, purified NSCCs or CSCs were cultured in a microfluidic chip and the expressions of CD133 cell-surface antigen marker were followed for a period of time. Figure 3A shows the typical
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Enrichment of CD133<sup>+</sup> CSCs and CD133<sup>−</sup> NSCCs through FACS. (A–C) Typical image of FACS sorting and efficiency. (A) Sorting of CD133<sup>+</sup> and CD133<sup>−</sup> cell subpopulation. (B) Typical enrichment efficiency of CD133<sup>+</sup> subpopulation from A. (C) Typical enrichment efficiency of CD133<sup>−</sup> subpopulation from A. (D–F) Sphere formation of CD133<sup>+</sup> and CD133<sup>−</sup> cells. (D) Typical image of sphere formations of CD133<sup>+</sup> cells. (E) Typical image of sphere formations of CD133<sup>−</sup> cells, bar = 100 μm. (F) Statistics in (D) and (E) at day 4 post inoculation (mean ± s.d., n = 3; *P = 0.00109).

The inter-conversion between CSCs and NSCCs is in a homoeostasis state

To further address the relationships between CSCs and NSCCs, initial cells from purified CSCs, NSCCs, and the mixture group were cultured, and the distributions of cell types were monitored by FACS over multiple generations of growth. In the purified CD133<sup>−</sup> NSCCs group, CD133<sup>−</sup> NSCCs were detected and the proportion was found to increase with generations (Figure 4A). However, in the purified CD133<sup>+</sup> CSCs group, the proportion of CD133<sup>−</sup> NSCCs was also expectedly found to increase with generations. Significantly, over a period of weeks, the CSC population of purified CSCs, NSCCs, and the mixture group were stabilised at around the 65% level typical of the unsorted SW620 cell line, indicating an intrinsic homoeostasis between CSCs and NSCCs (Figure 4A). The lines drawn in Figure 4 represent the best fitting of the data. Coupled with the in situ observational results, it is confirmed that CD133<sup>−</sup> NSCCs can spontaneously generate CD133<sup>+</sup> CSCs in in vitro cultures. Importantly, the de novo-created CD133<sup>+</sup> subpopulations are truly CSCs, as also defined by their cell-surface markers, the ability to form spheres, and the increase in radioresistance (similar to Figure 2). We repeated the studies in MCF-7 cells and got similar results (Supplementary Figure S3A). These results demonstrate that CSCs and NSCCs in SW620 and MCF-7 cell lines are in homoeostasis such that the proportion of these two cell types remains constant over many generations. The balanced inter-conversion between distinct cell types has profound impact on cancer therapy.
types may be biologically important and relevant for maintaining the heterogeneity of cancers.

The homoeostasis between CSCs and NSCCs is intrinsic and cannot be disturbed by high-dose ionising irradiation

To test the inter-conversion and the dynamic equilibrium between CSCs and NSCCs after irradiation, we exposed purified CSCs, NSCCs, and unsorted SW620 cells to \( \gamma \)-ray at single dose of 2 and 6 Gy and in fractions at 2 Gy \( \times \) 3. The results showed that irradiation did not disturb the final dynamic equilibrium (Figures 4B–D), although there was an initial perturbation on the homoeostasis, which leads to a transient increase of CD133\(^+\) CSC proportion 12 h post irradiation (Figure 4E). We repeated the experiments in MCF-7 cells and got similar results (Supplementary Figure S3B). These results indicated that the homoeostasis between CSCs and NSCCs is intrinsically controlled even after high dose of irradiation. This might explain the basis of local failure, which is a major therapeutic challenge after...
radiotherapy (Dalerba et al, 2007; Visvader and Lindeman, 2008; Clevers, 2011).

TGF-β1-induced EMT may have important roles in the intrinsic homoeostasis

The molecular mechanisms for the inter-conversion and the homoeostasis remain unknown. Epithelial mesenchymal transition, a key developmental programme that is often activated during cancer metastasis and can be induced by ectopic expression of Snail, Twist, or by exposing cells to the TGF-β1 (Andarawewa et al, 2007; Thiery et al, 2009; Vesuna et al, 2009), is directly linked with de novo generation of CSCs. We therefore exposed the purified NSCCs cells to TGF-β1 and quantified the dynamic proportion of CD133+ CSCs from CD133− NSCCs (Andarawewa et al, 2007; Thiery et al, 2009; Vesuna et al, 2009). The results showed that NSCCs supplemented with TGF-β1 significantly increased the de novo generation of CSCs and reached the dynamic equilibrium as early as 8 days post inoculation (P<0.05, Figure 5A).

In contrast, treatment with SB431542, a potent and specific inhibitor of TGF-β1 activin receptor-like kinase receptors, significantly decreased the de novo generation of CSCs in purified NSCCs cultures (P<0.05, Figure 5A).

Figure 3  In situ immunofluorescence of CD133 expressions. (A–C) Constructed microfluidic chip for in situ immunofluorescence of CD133 expressions. (A) The planform of a typical chip, white arrow indicates the reservoir, green arrow indicates the cell culture room of the chip, and purple arrow indicates the micro-channel of the chip, bar = 1 mm. (B) The cell culture room (indicated as green arrow) and the channel (indicated as purple arrow) of a typical microfluidic chip, bar = 200 μm. (C) The schematic diagram of a microfluidic chip. (D and E) Typical in situ transition of CD133+ CSCs from CD133− NSCCs (white arrows in E). (F and G) Typical CSC self-renewal (white arrows in G) and asymmetric division (indicated as one white and one yellow arrow in G). (H and I) Typical differentiation of CSCs into NSCCs (yellow arrows in I), bar = 50 μm for D–I. Yellow arrows indicate NSCCs and white arrows indicate CSCs. Images were merged with nuclei and CD133 expression patterns through Image-Pro Plus software (Media Cybernetics, Bethesda, MD, USA).
Figure 4 Intrinsic homeostasis between CD133+ CSCs and CD133− NSCCs. (A) Dynamic proportion of CSC subpopulation of purified CSCs, NSCCs, mixture of the two cell types, and unsorted SW620 controls over a period of 24 days. (B) Dynamic proportion of CSC subpopulation in purified CD133+ cells with or without irradiation. (C) Dynamic proportion of CSC subpopulation in purified CD133− NSCCs with or without irradiation. (D) Dynamic proportion of CSC subpopulation in unsorted SW620 cells with or without irradiation. (E) Details of data from the bracketed curve covering 0–48 h. Each data point represents mean ± s.d., n≥3.

In addition, treatment of unsorted SW620 cells with TGF-β1 and SB431542 showed a slight but significant difference in the CSC proportion (P<0.05, Figure 5A). Meanwhile, immuno-fluorescence assay of E-cadherin and Vimentin in TGF-β1-treated NSCCs showed a significant decrease in expression of the epithelial marker E-cadherin and a significant increase in expression of the mesenchymal marker Vimentin in the conversion process (Figure 5B for E-cadherin and Figure 5C for Vimentin). These results indicated that TGF-β1 may have important roles in the inter-conversion and the homeostasis between CSCs and NSCCs via activating the EMT process.

DISCUSSION

A key unresolved issue for cancer biology and therapy is whether the relentless growth of a tumour is driven by most of its cells or, as proposed by the CSC hypothesis, exclusively by a minor subpopulation capable of self-renewal, akin to the numerically rare normal stem cells that maintain tissues (Adams et al, 2007). For more effective cancer therapies, it is critical to determine which cancer cells have the potential to contribute to the disease progression. Currently, there are two major conflicting models (Clevers, 2011). One is the traditional stochastic (clone evolution) model, which is well documented and proposes that most cancer cells can proliferate extensively and metastasise. To this view, traditional cancer therapies have sought to eliminate as many cancer cells as possible (Shackleton et al, 2009). The other, however, is the CSC model. The model proposes a hierarchical organisation of cells within the tumour, in which a subpopulation of stem-like cells is responsible for sustaining tumour growth (Visvader and Lindeman, 2008). To this view, anti-tumour treatments are specifically designed to target CSCs, although theoretically unable to cause rapid shrinkage of tumour lesions, it might nonetheless achieve long-term disease eradication by exhausting self-renewal and growth potential of cancer tissues (Dalerba et al, 2007). Our results clarified the inter-conversion in situ between CSCs and NSCCs (Figure 3). In addition, the inter-conversion between CSCs and NSCCs is also found in a homeostasis state (Figure 4A). To maintain a stable equilibrium, the rates of CSC differentiation, self-renewal, and asymmetric division should be balanced by the rate of transitions of CSCs from...
NSCCs, which might depend on the proportion of CSCs in the population. These results, together with several other recent studies (Mani et al., 2008; Morel et al., 2008; Meyer et al., 2009; Liang et al., 2010; Chaffer et al., 2011; Iliopoulos et al., 2011), indicate that some cancer cells retain the capacity to convert to a more primitive, stem-like state when adapting to changing conditions, indicating a need to reconcile the current stochastic and CSC models of tumour progression (Alison et al., 2011; Clevers, 2011).

The microfluidic chip used in present study was designed to overcome several difficulties commonly encountered under in situ cell observations. First, positioning and relocating of target cells on a micrometre scale are the basis of in situ observation. Cells cultured in normal dish or chamber slide cannot achieve the high precision goal. Second, cells cultured in dishes or chamber slide are easily movable when changing the medium. In in situ observations, immunostaining, washing, and reloading of the medium will lead to significant movement of the cells being followed. Third, shear force needs to be minimised in all of the procedures to ensure little mechanical damage to cells. With the designed chips and a Live Cell Station, we clarified the inter-conversion between CSCs and NSCCs in situ (Figure 3).

Irradiation is a widely used treatment modality for various solid tumours and about 60% of cancer patients receive radiation therapy (Garcia-Barros et al., 2003). The CSC hypothesis suggests that standard radiotherapy can effectively kill NSCCs but CSCs largely survive because of the intrinsic radioreistance and thereafter reinitiate the bulk of the tumour (Dalerba et al., 2007; Cui et al., 2011; Iliopoulos et al., 2011). Our experimental results show that the dynamic equilibrium in a given cell group might be intrinsic and might be resistant to disturbance by external factors such as high-dose irradiation (Figures 4B–D). Logically, due to the radioreistant nature of CSCs, CSC proportion in tumour is expected to be transiently higher after irradiations (Figure 4E). However, given the equilibrium for homoeostasis control of the cell subpopulations, it is possible that higher CSC proportion might increase their differentiation into NSCCs to repopulate tumour cells. This may indicate a possible mechanism of local failure, which is one of the major therapeutic challenges after radiotherapy (Visvader and Lindeman, 2008).

The molecular mechanisms for the inter-conversion and the homoeostasis between CSCs and NSCCs largely remain unknown. It is well known that co-expression of pluripotency markers, such as Oct3/4, Sox2, c-myc, Klf4, Nanog and lin28, can reprogram somatic cells into pluripotent embryonic stem-like cells (Takahashi and Yamanaka, 2006; Yu et al., 2007). Likewise, studies also showed that single or combined overexpression of stemness factors, including Oct-4 and Nanog, were associated with cancer stem-like properties and EMT induction (Chiou et al., 2010; Chen et al., 2012; Kumar et al., 2012). Epithelial mesenchymal transition, a key developmental programme that is often activated during cancer metastasis and can be induced by ectopic expression of Oct-4 (Chiou et al., 2010), Twist (Vesuna et al., 2009), by inhibition of proteasome (Kim et al., 2011), or even by treatment with irradiation and/or TGF-β (Andarawewa et al., 2007), is directly linked with de novo generation of CSCs (Mani et al., 2008; Thiery et al., 2009). As inhibition of proteasome can cause EMT and generate cells with stem-like properties (Kim et al., 2011), the low proteasome activities might be also involved in the de novo generations of CD133+ CSCs from CD133− NSCCs. In addition, irradiation can activate EMT and evoke a rapid inhibitory effect on proteasome function in a variety of cell types (Pajonk and McBride, 2001; Andarawewa et al., 2007), therefore, despite of the radioreistance nature of CSCs, transient induction of CD133 accumulation via EMT activation and/or proteasome inhibition might be also involved in the transient increase of CD133+ cells after irradiations (Figure 4E). Our results showed that irradiation and TGF-β treatment can accelerate the inter-conversion and homoeostasis between CSCs and NSCCs (Figures 4C and 5A), with significant decrease in expression of the epithelial marker E-cadherin and significant increase in expression of the mesenchymal marker Vimentin in the conversion (Figures 5B–C), suggesting EMT might have important roles in the inter-conversion and homoeostasis between CSCs and NSCCs.

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