

Cell-of-Origin of Cancer versus Cancer Stem Cells: Assays and Interpretations

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Abstract

A tumor originates from a normal cell that has undergone tumorigenic transformation as a result of genetic mutations. This transformed cell is the cell-of-origin for the tumor. In contrast, an established clinical tumor is sustained by subpopulations of self-renewing cancer cells operationally called cancer stem cells (CSC) that can generate, intracлонally, both tumorigenic and nontumorigenic cells. Identifying and characterizing tumor cell-of-origin and CSCs should help elucidate tumor cell heterogeneity, which, in turn, should help understand tumor cell responses to clinical treatments, drug

resistance, tumor relapse, and metastatic spread. Both tumor transplantation and lineage-tracing assays have been helpful in characterizing these cancer cell populations, although each system has its strengths and caveats. In this article, we briefly review and summarize advantages and limitations of both assays in support of a combinatorial approach to accurately define the roles of both cancer-initiating and cancer-propagating cells. As an aside, we also wish to clarify the definitions of cancer cell-of-origin and CSCs, which are often interchangeably used by mistake. *Cancer Res*; 75(19); 4003–11. ©2015 AACR.

Introduction

Epithelial cancers are complex and exhibit intertumoral and intratumoral heterogeneity. Identifying specific cell types that initiate and sustain tumorigenesis is key to addressing tumor cell heterogeneity and other outstanding tumor biology questions. Cancer-initiating cell, or the cell-of-origin of cancer, is the normal cell that receives the first cancer-causing mutations. In other words, the cancer-initiating cell founds a future clinical tumor. Cancer stem cells (CSC), on the other hand, are the cells that maintain tumor propagation (1–3). Aptly referred to as cancer-propagating cells, CSCs are defined by two attributes, self-renewal and multipotency. The phenotypes between cancer-initiating cells and cancer-propagating cells may differ and dynamically change and, in most cases, the relationship between the two is not well understood. Two assays have been helpful in characterizing these two cell types: transplantation assays and lineage-tracing assays (Fig. 1). The serial tumor transplantation assay is the current "gold standard" for identifying CSCs because it can assess both self-renewal and multipotency. Transplantation assays can also be used to determine the cell-of-origin of cancers. Lineage tracing is the current gold standard for defining the cell-of-origin of transformation in mouse models. Lineage tracing is also being used to provide insight into the proliferative potential and fate of stem cells

during tumor formation as evidenced by recent progress in identifying CSCs in solid tumors.

The Transplantation Assay

In the transplantation assay, tumor cell populations are fractionated and xenografted into immunocompromised mice. When identifying CSCs, cancer cell subpopulations are sorted using FACS based on relatively specific or presumed CSC markers followed by limiting dilution assay (LDA) and serial tumor transplantations to determine the CSC frequency and multilineage potential of a given marker phenotype (Fig. 1A, a). Populations of CSC marker-positive cells that give rise to serially transplantable tumors that histologically recapitulate the cellular heterogeneity of the parental tumors can therefore be classified as CSCs, whereas populations of CSC marker-negative cells with no or limited tumor-propagating activity can be excluded from the CSC candidates (Fig. 1A, a). These assays have demonstrated the existence of CSCs in human cancers, including acute myeloid leukemia (AML), chronic myeloid leukemia (CML), breast cancer, glioblastoma, colorectal cancer, and others (1–3).

Historically, in the early 1950s, it was shown that a small fraction of cells in murine tumors could withstand freeze-thawing as indicated by proliferation *in vitro*, providing early evidence for functional heterogeneity in sarcoma cell subpopulations (4). Subsequent quantitative transplantation assays determined that 1 of 27 viable cells was capable of giving rise to a tumor when cells from a murine sarcoma tumor, S37, were xenotransplanted into 4- to 6-week-old albino mice (5). Direct proof for the existence of leukemic stem cells (LSC) was provided in the mid-1990s (reviewed in ref. 3), and in the 2000s, evidence for CSCs was extended to human solid tumors. It was first shown that in human breast cancer, as few as 100 cells bearing the CD44⁺CD24^{-/low}Lin⁻ cell surface marker profile could regenerate serially transplantable tumors in mice (6). Shortly thereafter, xenotransplantation assays evinced CSCs in human brain tumors, with the CD133⁺ tumor cell fraction

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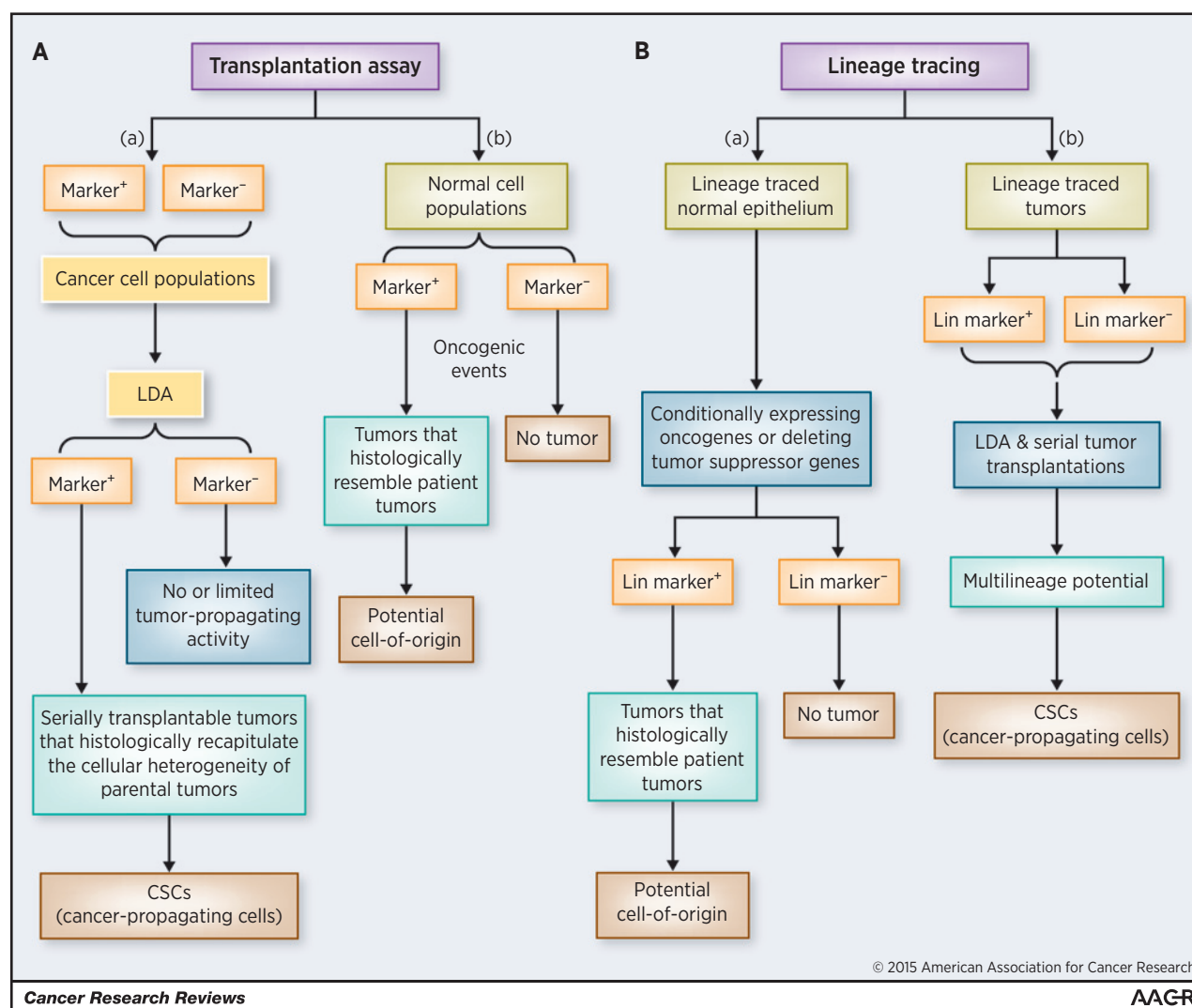


Figure 1.

A comparison of transplantation and lineage-tracing assays. A, tumor transplantation assay. LDA can be used in combination with serial transplantations to assess CSC abundance and properties in a candidate marker-positive tumor cell population (a). The transplantation assay can also be used to determine cell-of-origin in cancers (b). B, lineage-tracing assay. This is most commonly used to determine the potential cell-of-origin for a cancer. In a specific normal cell population, transformation events can be introduced via activation of oncogenes or inactivation of tumor suppressor genes. Labeled tumors can then be traced back to a specific cell-of-origin (a). Lineage tracing can also be used to determine and/or authenticate the CSC properties of the marked cell population in the established, traced tumor (b).

containing cells capable of tumor regeneration in nonobese diabetic/severe combined immunodeficiency (NOD/SCID) mouse brains (7).

The key elements in properly using the xenotransplantation assay to identify and characterize CSCs in human tumors are to perform rigorous LDA and serial tumor transplantations (Fig. 1A, a). In the LDA, CSC frequency is measured by transplanting increasingly diluted single-cell preparations. After tumor regeneration is evaluated for each cell dose, the frequency of cancer cells present in a given cell population that can regenerate a xenograft tumor can be approximated. For this reason, CSCs are also frequently called tumor-initiating cells, which is actually not very accurate and should rather be termed tumor-regenerating cells. In subsequent serial transplantations, true CSCs or

CSC-enriched population should be able to perpetuate the xenograft tumors for multiple generations, thus attesting that these particular cells have an inherently unlimited life span when propagated *in vivo* (Fig. 1A, a). Important, LDA combined with serial tumor transplantations helps assess one of the most important biologic traits of CSCs, that is, self-renewal *in vivo*. As an example, in a recent study, prostate-specific antigen (PSA)-positive (PSA⁺) and PSA^{-/lo} human prostate cancer cells were separated and used in serial tumor transplantations (8). The study revealed that the PSA^{-/lo} population could regenerate and propagate xenograft tumors virtually indefinitely, whereas the PSA⁺ prostate cancer cell population could only propagate xenograft tumors for about three generations (8). This study illustrates that the serial tumor transplantation assay has the

ability to compare isogenic subpopulations under identical experimental conditions to determine differences in tumor regeneration and long-term tumor-propagating capacities. Similar serial transplantation studies have demonstrated that human breast (6) and colon (9) CSCs can initiate serially transplantable tumors and thus can self-renew in immunodeficient mice.

Transplantation assays can be used to probe the potential cell-of-origin of cancer as well (Fig. 1A, b). In this scenario, normal cell subpopulations are sorted via FACS based on specific markers followed by introduction of oncogenic events (overexpressing oncogenes and/or knocking out tumor suppressor genes) and subsequent survey of differential tumor formation in xenotransplantation assays. When a marker-positive population gives rise to tumors that histologically resemble parental or patient tumors, cells within this population can then be considered as a potential cell-of-origin for that specific type of cancer (Fig. 1A, b). One example comes from a recent study that demonstrates that the basal epithelial cells from primary benign human prostate tissue, upon tumorigenic transformation, can initiate prostate cancer in immunodeficient mice (10). The authors developed a system whereby naïve adult human prostate epithelium is directly transformed with genetic alterations commonly found in human prostate cancer. When primary human prostate basal and luminal cells transduced with lentivirus carrying red fluorescent protein were combined with murine urogenital sinus mesenchyme cells in Matrigel and injected subcutaneously into NOD/SCID/IL-2R γ^{null} (NSG) mice, outgrowths were observed only from basal cells (10). Important, when the lentivirus cocktail included both activated (myristoylated) AKT and ERG, basal cell but not luminal cell-derived lesions fulfilled the histologic criteria for the diagnosis of high-grade precursor lesion (10). With the addition of AR (androgen receptor) to the mix, adenocarcinomas developed from transformed basal cells but not luminal cells (10). This study (10) thus indicates that the human basal prostate epithelial cells can function as a potential cell-of-origin for prostate cancer. Using similar transplantation assays, Taylor and colleagues also demonstrated that basal epithelial cells could act as cells-of-origin for prostate cancer (11). One word of caution when using transplantation assays to study cancer cell-of-origin is that a positive outcome only indicates that a specific cell population CAN function as the target of tumorigenic transformation but may not necessarily BE the actual cell-of-origin for cancer *in vivo*.

For obvious reasons, human tumor cells can only be xenotransplanted to immunodeficient mice to assess their inherent CSC properties. As a result, a major disadvantage of cell transplantation assays is that dissociated single cells may not behave the same way as they do in their natural tissue microenvironment (i.e., niche), thereby misrepresenting the existence or abundance of CSCs (see below). By teasing apart the intact tissue to resolve subpopulations, we inevitably change the cells' metabolism, their apparent role in the tissue hierarchy, and potentially their developmental trajectory. Therefore, it may not be certain whether transplantation assays demonstrate selection of phenotypically plastic cells that survive and proliferate in the new environment or whether they are actually assaying the implicit CSC traits. In addition, solid tumor cells exist in complex microenvironments that are not readily modeled by transplantation because xenotransplants differ in architecture and stroma compared with their native environment. Another caveat associated with xenotransplantations lies in the

lack of an immunocompetent microenvironment such that many have argued that the transplantation-based CSC assays may not assess the intrinsic properties of stem cells but may instead be assessing the ability of transplanted human cancer cells in evading immune surveillance. However, this may be a circular argument—it is precisely because CSCs lack the expression of differentiation markers such as MHC molecules that they can better escape host immune-mediated attack, take root, and initiate and propagate human tumors in mice (12).

Understandably, the outcome of xenotransplantation experiments can be influenced by many variables, including the level of malignancy (or differentiation) of donor human tumors and the level of immunodeficiency of recipient mice (2). For instance, the frequency of human melanoma CSCs was found to be as high as 15% to 25% when assayed in NSG mice compared with 1 in 10⁵ cells in NOD/SCID mice (13). The high frequency of melanoma CSCs in NSG mice has been interpreted by many as evidence for lack of tumorigenic hierarchy in melanoma. However, in that study (13), most melanoma samples used were very advanced high-grade tumors and it is well-known that advanced, undifferentiated human cancers are highly enriched in CSCs (1–3, 8). Indeed, when early stages of melanoma specimens were later used in CSC studies, it was found that CD271⁺ melanoma cells identify rare melanoma CSCs (14). Along the same line, in a syngeneic transplantation study of pre-B/B lymphoma cells from E μ -myc transgenic mice, a very high frequency of the tumor-initiating cells was observed (15), which again was construed by many as evidence to refute the CSC concept. However, the E μ -myc lymphoma cells are known to be extremely aggressive, resembling undifferentiated human tumors in which CSCs are greatly enriched. Recent lineage-tracing studies in mouse models of tumors have also provided direct evidence for CSCs (see below).

The Lineage-Tracing Assay

The lineage-tracing assay is mostly commonly used to determine the potential cell-of-origin of tumors (Fig. 1B, a), although it can also be used to study CSCs (Fig. 1B, b). In the lineage-tracing assay, use of different cell-specific promoters allows distinct cell subpopulations to be labeled, allowing tracking of a single cell-derived clone in animals (see below). The ability to resolve individual cell fate is the greatest advantage of this assay. To determine cell-of-origin, normal (epithelial) cells are genetically labeled followed by introduction of activating and inactivating mutations in various oncogenes and tumor suppressors in the same cell type. The fully transformed cell that forms a tumor can then be traced and identified as the cellular source of the tumor (Fig. 1B, c). On the other hand, in the established, traced tumors, single marked tumor cells can be purified out and used in the LDA and serial tumor transplantations to determine whether the lineage-traced tumor cells have true CSC properties, that is, self-renewing and long-term tumor-propagating activity (Fig. 1B, d). This latter tracing strategy can also be adapted to dissect tumor cell heterogeneity in cultured cancer cells and human xenograft tumors. For example, a PSA promoter was used to drive reporters (GFP and RFP) in a lentiviral vector, which was used to infect cultured as well as xenograft prostate cancer cells and to separate the PSA^{-lo} and PSA⁺ prostate cancer cells (8). When traced *in vitro* and *in vivo*, the PSA^{-lo} prostate cancer cells were found

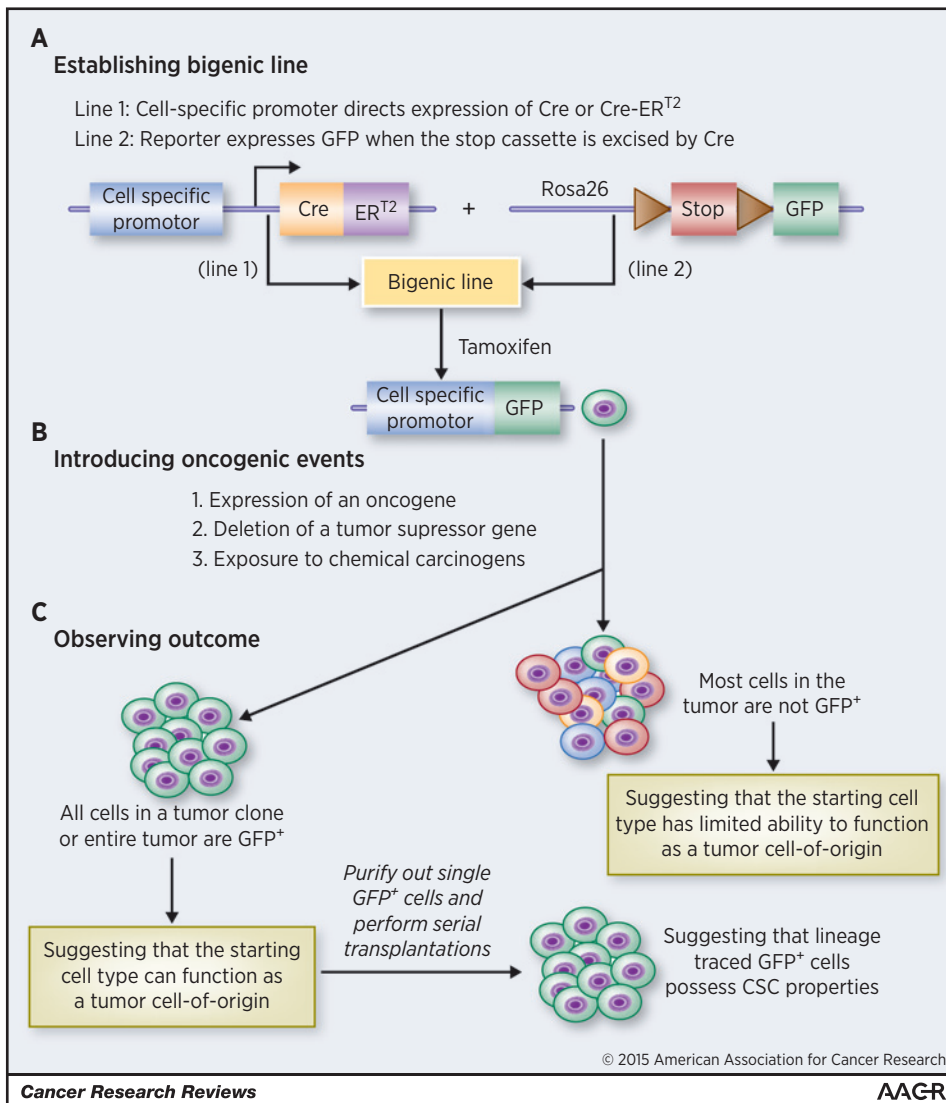


Figure 2. Schematic for a lineage-tracing study. Three main steps are outlined. See text for detailed descriptions.

to be able to undergo asymmetric cell division generating PSA⁺ cells under time lapse microscopy as well as in serially transplanted tumors (8). Similarly, a Wnt reporter was used to trace colorectal CSCs and to demonstrate that the secreted soluble molecules from the neighboring myofibroblasts activate the Wnt signaling in these CSCs (16).

Figure 2 depicts a basic scheme for performing a lineage-tracing study. The first step is to establish a bigenic mouse line by crossing an inducible Cre line, which expresses the Cre recombinase, with a "generic" reporter line to achieve cell-specific labeling (Fig. 2A). For the inducible Cre transgenic (Tg) line, a cell-type-specific gene promoter is used to drive the expression of modified, tamoxifen-inducible Cre (CreER or CreER^{T2}). The gene promoters can be stem cell-specific (e.g., *p63*, *Lrig1*, *Lgr5*, *Sox9*, *Nkx3.1*, etc.) or the ones active in differentiated lineages (e.g., *K8* and *K18*). Promoter can be endogenous, in which CreER or CreERT2 expression cassette is knocked into the endogenous promoter locus. Alternatively, an exogenous promoter can be used to drive Cre expression in a conventional Tg line. An example is the use of human PSA gene

promoter to drive Cre expression in a Tg model to show that regenerated prostatic epithelial cells upon castration—androgen supplementation—were derived from the pre-existent luminal cells (17). In the second mouse line, a reporter (either fluorogenic such as GFP and RFP or colorimetric such as β -galactosidase) is flanked by a *loxP-STOP-loxP* sequence (Fig. 2A). In the bigenic mice, tamoxifen activates Cre expression via excising *loxP-STOP-loxP*, which in turn activates the reporter in cells that express the promoter activity (Fig. 2A). Doxycycline-inducible TetO-Cre system or orthotopic adenoviral delivery of lineage-specific Cre recombinases (AdCre) can also be used to express Cre in specific cell types.

To study tumor development, the second step is to introduce oncogenic events, which can be either genetic or chemical, to the specifically labeled cell types (Fig. 2B). For genetic approaches, this is accomplished by crossing the above bigenic line with the third Tg line that overexpresses certain oncogenes (*Myc*, *Ras*, *Tcf*, etc), or has some tumor suppressors (e.g., *Pten*, *Rb*, *p53*) deleted. For chemical carcinogenesis, the bigenic animals are challenged by chemical carcinogens (e.g., DMBA)

known to cause cancer in the specific tissues/cells. The molecular basis of chemical carcinogenesis is still genetic—for instance, DMBA mainly causes mutations in *K-ras*. In the final step of lineage tracing (Fig. 2C), tumor development is observed by monitoring the expression pattern of the trace label. For instance, if all cells in a tumor clone or the entire tumor is label (e.g., GFP)-positive, it suggests that the specific cell type marked by GFP CAN function as a cancer cell-of-origin in that specific context. These GFP⁺ tumor cells can be purified out in serial tumor transplantations to further demonstrate their CSC or tumor-propagating activities (Fig. 2C). On the other hand, if the majority of tumor cells are GFP⁻, it would suggest that the initially traced cell type does not function as the cell-of-origin for the tumor development (Fig. 2C).

Recently, three lineage-tracing studies (18–20) provided support for the CSC model across three different types of solid tumors—skin, intestinal, and brain (Fig. 3). In one study (18), lineage tracing was used to pinpoint a putative endogenous glioma stem cell population that plays a pivotal role in tumor maintenance and recurrence after chemotherapy (Fig. 3A). A nestin- Δ TK-IRES-GFP transgene labeled quiescent subventricular zone (SVZ) adult neural stem cells and the labeled GFP⁺ cells could be ablated by ganciclovir (GCV) through the action of the truncated thymidine kinase (TK; Fig. 3A, a). When this Tg line was crossed with glioma-prone mouse line called Mut7 (induced by concerted deletion of three tumor suppressors, i.e., *Nf1*, *p53*, and *Pten* in GFAP-expressing cellular compartment), a subset of endogenous glioma tumor cells was also labeled by GFP and these GFP⁺ cells could also be ablated by GCV (Fig. 3A, b). Interestingly, most GFP⁺ glioma cells were Sox2⁺ and not dividing (i.e., Ki67⁻) whereas most Ki67⁺ glioma cells were GFP⁻ (Fig. 3A, b). Temozolomide, a drug used to treat patients with glioma, eliminated most GFP⁻/Ki67⁺ tumor cells leaving behind a significant fraction of GFP⁺/Ki67⁻ quiescent mouse glioma cells, which mediated recurrent tumor formation (Fig. 3A, b). Remarkably, ablation of the GFP⁺ cells with chronic GCV administration significantly retarded tumor growth, leading to extended animal survival, and combined temozolomide and ganciclovir treatment impeded tumor development (Fig. 3A, c; ref. 13). GCV administration also reduced tumor growth in secondary tumor transplants (Fig. 3A, d). This lineage-tracing study demonstrates that a relatively quiescent subset of endogenous glioma cells, with properties similar to those proposed for CSCs, is responsible for sustaining long-term tumor growth.

In the second study (19), use of a multicolor Cre reporter R26R-Confetti and the β -naphthoflavone-inducible Ah-Cre mouse strain demonstrated that the crypt stem cell marker *Lgr5* also marked a subpopulation of adenoma cells induced by loss of *Apc* (Fig. 3B, a). When R26R-Confetti was crossed into the *Lgr5* knock-in Cre-expressing mouse strain, tamoxifen injection allowed single *Lgr5*⁺ stem cells to randomly adopt one of the four fluorescent colors encoded in the R26R-Confetti allele. The formation of adenomas was derived from individual *Apc*-mutant stem cells. In addition, the location of the labeled *Lgr5*⁺ cells was near the base of the wedge-shaped adenoma segments, concurrent with the crypt stem cell niche (Fig. 3B, a). Transcriptional profiles and clonogenic potential of *Lgr5*-GFP^{hi} cells suggested that this population constituted multipotent stem cells. The fate of *Lgr5*⁺ adenoma cells in individual clones was back-traced *in vivo*, and it was concluded that the cells were derived from a single adenoma stem cell (Fig. 3B, b).

The third lineage-tracing study used a classical chemical 2-stage carcinogenesis model (20), in which skin papillomas were initiated by the carcinogen DMBA and then propagated by tumor promoter TPA (Fig. 3C, a). The bigenic line, K14CreER/Rosa-YFP, was created by crossing K14-driven CreER line with the Rosa26-YFP reporter line (Fig. 3C, a). In the presence of tamoxifen, all K14-expressing basal keratinocytes would be labeled as YFP⁺. Upon DMBA/TPA treatment and tamoxifen application, cells within the papillomas were labeled and the YFP⁺ tumor cells were capable of generating all cell types that comprised the tumor (Fig. 3C, a). Interestingly, the majority of labeled tumor cells in benign papillomas had limited proliferative potential, whereas a particular fraction had the capacity to persist long term (20). Specifically, the more persistent population displayed stem cell-like characteristics and cycled twice per day, whereas a slower cycling population gave rise to terminally differentiated tumor cells. Data from 3-dimensional (3D) reconstruction using confocal analyses of clones indicated that papillomas were sustained by a cellular hierarchy in which a minor population of tumor cells with stem cell-like properties gave rise to a more transient progenitor cell pool (Fig. 3C, c).

Lineage tracing has now been used to identify probable cells-of-origin for many mouse models of cancers, including intestinal, prostate and basal cell carcinomas, brain and breast tumors, as well as pancreatic ductal adenocarcinoma. In prostate cancer, for example, the lineage-tracing assay was used to identify a rare luminal epithelial population, termed CARNs (castration-resistant *Nkx3.1*-expressing cells) with stem cell properties during prostate regeneration in mice (21). These cells were marked using a genetically engineered mouse line in which an inducible Cre^{ERT2} recombinase was put under the control of the endogenous promoter for *Nkx3.1*, a prostate tumor suppressor. After Cre activation by tamoxifen treatment in castrated *Nkx3.1CreERT2*^{+/+}; *R26R-YFP*^{fl/fl} male mice, YFP expression was observed in luminal epithelial cells, corresponding to lineage-marked CARNs. All CARNs in the regressed prostate were strictly luminal and growth-quiescent. However, after regeneration upon testosterone treatment, the percentage of lineage-marked cells increased 9-fold, indicating their proliferative potential, and, important, basal cells appeared, indicating that CARNs contained bipotential progenitors. Subsequent single-cell transplantation of lineage-marked CARNs further indicated the multipotency of these cells. The authors further demonstrated that by crossing the compound reporter mice with *Pten* mutant mice, the CARNs could function as cells-of-origin for prostate cancer (21). The same group later showed that basal cells, upon loss of *Pten*, gave rise to tumors with luminal phenotypes, but they noted that these basal cells displayed substantial phenotypic plasticity when removed from their endogenous tissue microenvironment (22). Hence, the authors stressed that transplantation-based assays have a tendency to overestimate the frequency of putative stem cells and that genetic lineage tracing *in vivo* should be preferably used for identification of potential tumor cell-of-origin (22).

Another group genetically marked mouse prostate basal cells and luminal cells in adult mice using K14-CreER and K8-CreER^{T2}, respectively, to further interrogate the cellular origin of prostate cancer (23). It was found that prostate basal cells only generated basal cells, whereas luminal cells only generated luminal cells, suggesting that adult prostate epithelial lineages are maintained

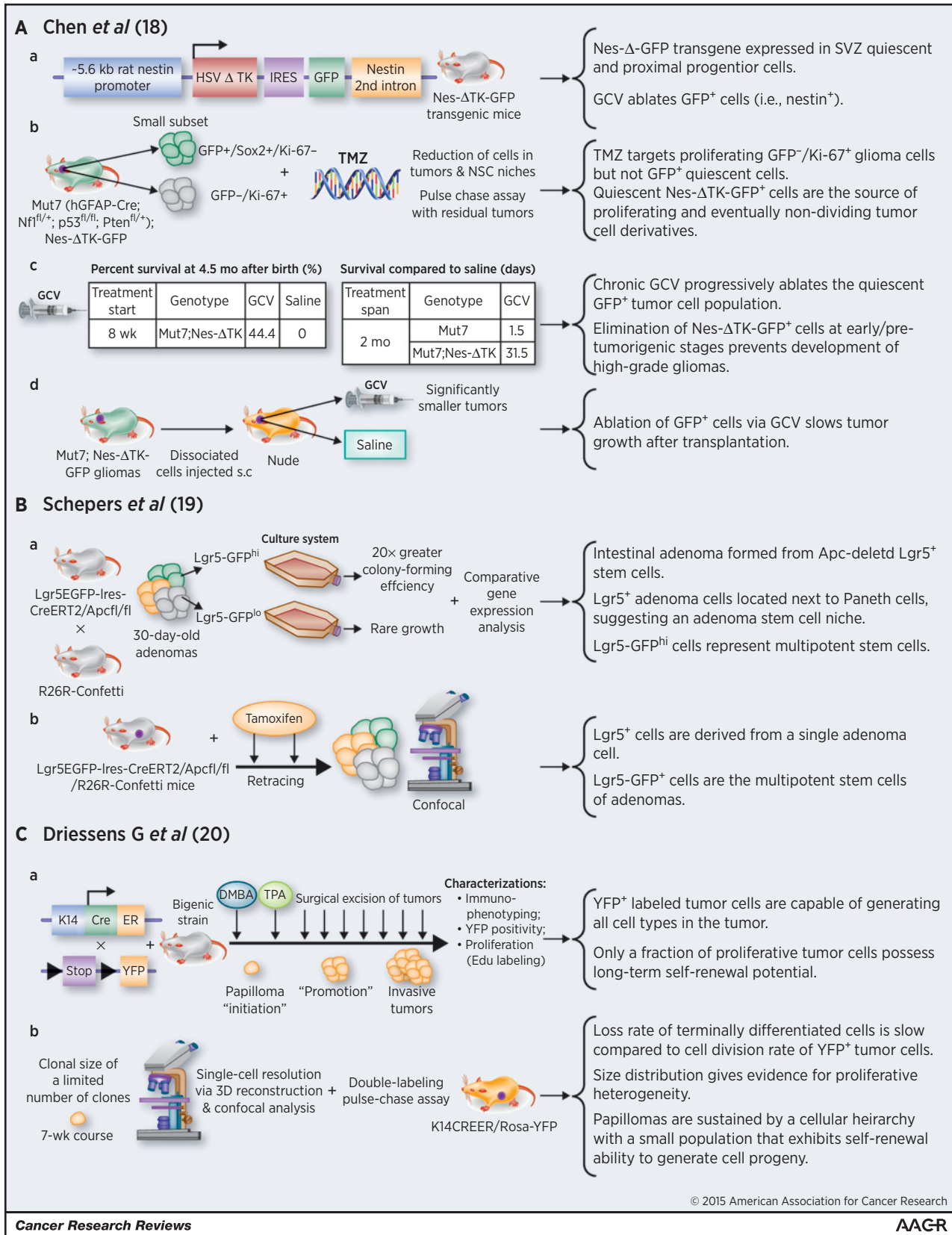


Figure 3. Summary of three recent lineage-tracing studies providing support for the CSC model. Details for each study are discussed in the text. The lineage-tracing tumor models are presented on the left and main outcomes and conclusions summarized on the right.

by unipotent progenitors or self-duplication of epithelial cells. *Pten* was then knocked out in both cell types, and interestingly, prostatic intraepithelial neoplasia, a precursor lesion to prostate cancer, appeared in both mice but only after a long latency in the K14-CreER mice, suggesting that basal cells had to convert into luminal cells in the context of tumor development by *Pten* deletion. This study demonstrates that both prostate basal and luminal cells can serve as the cellular origin for prostate cancer.

As in all other techniques, there are caveats and problems associated with lineage tracing. First of all, lineage tracing can only be conducted in mice and there are fundamental differences between human and rodent organs and cells. Take prostate again, mouse prostate has four distinct lobes that do not exist in the human counterpart. Mouse prostate does not even express PSA, the most "important" molecule in defining the prostate as a male glandular organ and in defining fully differentiated luminal epithelial cells. Also, somatic mouse cells possess high telomerase activity and express significantly longer telomeres than the human cells, suggesting that mouse cells in most lineages may never undergo true terminal differentiation. These latter molecular features underlie the reasons why rodent cells are highly susceptible to spontaneous immortalization as well as experimental tumorigenic transformation. Consequently, results with mouse studies should never be directly equated to human systems and always be put in appropriate context.

Second, the labeling efficiency in lineage-tracing studies is highly variable depending on the Cre- or reporter-driving promoters and generally low and the results may oftentimes be subject to alternative interpretations. When endogenous promoters are used, the promoter activity in less differentiated cells may not be strong enough to turn on the transgene, leading to low efficiency and spurious interpretations. In the example presented in Fig. 4, when CreER is driven by the

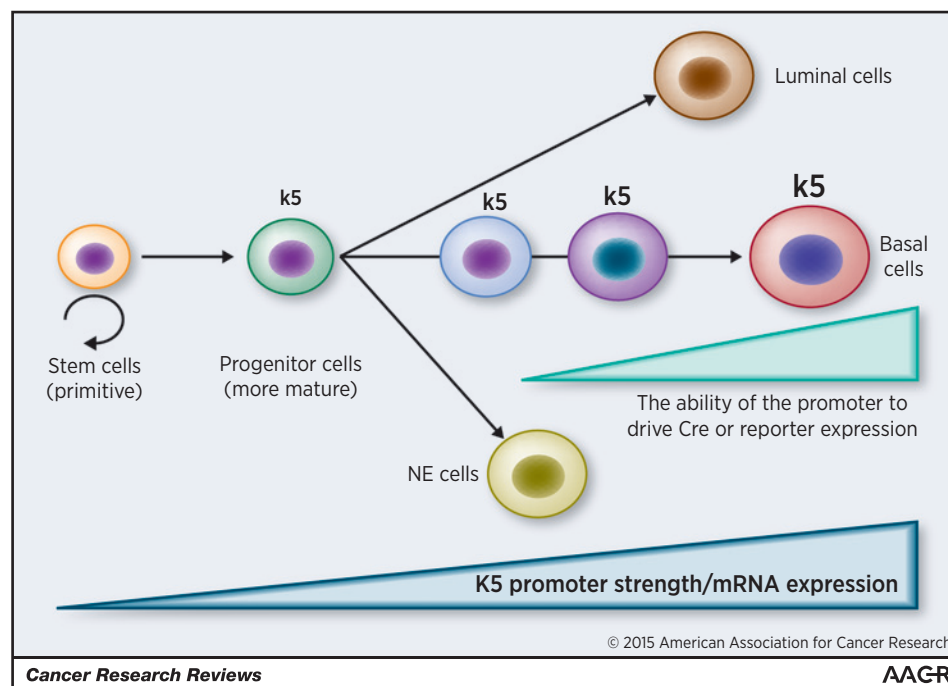
endogenous k5 promoter, lineage-tracing studies in adult mice may lead to the conclusion that k5-expressing (basal) cells can only regenerate more k5-positive basal cells. However, in multipotent progenitor cells that have the ability to differentiate into not just k5 cells but also luminal or even neuroendocrine cells because they have just started expressing k5 mRNA and the k5 promoter activity in these progenitor cells is too weak to activate the Cre, these cells will not be labeled (Fig. 4). In other words, only more differentiated cells that have already undergone lineage specification will be tagged by the reporter (Fig. 4), leading to inaccurate or even erroneous conclusions. Along this line, when exogenous or heterologous promoters are used in lineage tracing, they will randomly integrate into the genome, resulting in patterns of expression different from the endogenous gene. Furthermore, such promoters are likely regulated by quite different mechanisms than the endogenous promoters. In some cases, promoters exhibit some expression in tissues outside of those predicted, due to regulatory elements or read-through transcripts at the site of insertion.

Third, when lineage tracing is combined with mouse tumor models to elucidate cell-of-origin, there exists another problem. Most human epithelial cancers develop through decades of clonal evolution and accumulation of genetic mutations and epigenetic alterations. However, in mouse models of human cancer, the promoter is instantly turned on, leading to all-at-once genetic defects in an entire population of cells, a phenomenon fundamentally unlike the sequential acquisition of mutations found in most human cancers. Ideally, a cancer model should recapitulate the natural history of the disease by introducing a low frequency of sporadic mutations at a defined time.

Finally, the remaining construct and its insertional effects must be optimized. In most inducible lines, in which there is a single element to control Cre, the system frequently becomes

Figure 4.

Potential problems associated with lineage tracing. In this example, primitive stem cells with self-renewing activity do not express k5, whereas more mature progenitor cells start expressing low levels of k5 mRNA but the promoter activity is not strong enough to drive Cre or reporter gene expression. Hence, the promoter strength in less differentiated cells may not be strong enough to reach the labeling threshold, thereby failing to label the true primitive stem cells that possess the ability to undergo multilineage differentiation. NE, neuroendocrine.



leaky, having minor but detectable Cre activity in the absence of the inducer, resulting in spontaneous background recombination. In some cases, an alternative transgenic line, *AhcreER^T*, can be used to eliminate background recombination via controlling Cre activity transcriptionally both by Ah promoter and by tamoxifen binding (24). In addition, transgene insertion of Cre recombinase under the control of a specific promoter may alter the function of the endogenous locus via activation or silencing. Incomplete incorporation of regulatory elements into the driver construct or alternatively unexpected excision can also occur (25). *LoxP*-flanked target genes can differ dramatically with respect to their sensitivity to Cre-mediated recombination (26). Finally, Cre activity can be modified by strain genetic background and variable maternal/paternal germline expression can occur, highlighting the need for animal model optimization.

Concluding Remarks and Perspectives

The preceding discussions highlight the varying conclusions that may reflect differences and limitations in each assay used. A combinatorial approach of the two assays has the potential to lead to a better understanding of the cellular origins of cancer and CSCs and the development of more effective cancer therapies. A major consideration in performing both CSC and tumor cells-of-origin studies is the emergence of CSCs via cellular dedifferentiation (reviewed in detail in ref. 2). Several recent studies have demonstrated that non-CSCs can acquire CSC-like activity under certain conditions (27–30). For instance, many aggressive CSCs within individual tumors can be newly derived from their non-CSC counterparts, and this dedifferentiation may occur continually during the development of the tumor. In melanoma, differenti-

ated cancer cells can dedifferentiate into cells resembling embryonic stem cells that organize into vessel-like structures (30). In breast cancer, CSCs exist in distinct mesenchymal-like and epithelial-like states (27). Remarkably, these two populations of CSCs manifest different locations in the tumors and functional activities: while mesenchymal-like CSCs (CD24⁻CD44⁺) are mainly localized at the invasive tumor front and are largely quiescent, the epithelial-like CSCs (ALDH⁺) are located more centrally and are highly proliferative (30). Understanding the plasticity of CSCs and identifying the subpopulations of non-CSCs that are poised to convert to CSCs (2) should greatly facilitate the efforts in dissecting tumor cell heterogeneity and developing CSC-specific therapeutics. It has become clear that to eradicate cancer and prevent relapse, both CSCs and their less tumorigenic progeny must be targeted.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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References

- Visvader JE. Cells of origin in cancer. *Nature* 2011;469:314–22.
- Tang DG. Understanding cancer stem cell heterogeneity and plasticity. *Cell Res* 2012;22:457–72.
- Kreso A, Dick JE. Evolution of the cancer stem cell model. *Cell Stem Cell* 2014;14:275–91.
- Passey RD, Dmochowski L, Lasnitzki I, Millard A. Cultivation *in vitro* of frozen and desiccated mouse tumour tissues. *Br Med J* 1950;2:1134–6.
- Hewitt HB. Studies of the quantitative transplantation of mouse sarcoma. *Br J Cancer* 1953;7:367–83.
- Al-Hajj M, Wicha MS, Benito-Hernandez A, Morrison SJ, Clarke MF. Prospective identification of tumorigenic breast cancer cells. *Proc Natl Acad Sci USA* 2003;100:3983–8.
- Singh SK, Hawkins C, Clarke ID, Squire JA, Bayani J, Hide T, et al. Identification of human brain tumour initiating cells. *Nature* 2004;432:396–401.
- Qin J, Liu X, Laffin B, Chen X, Choy G, Jeter CR, et al. The PSA(-/lo) prostate cancer cell population harbors self-renewing long-term tumor-propagating cells that resist castration. *Cell Stem Cell* 2012;10:556–69.
- O'Brien CA, Pollett A, Gallinger S, Dick JE. A human colon cancer cell capable of initiating tumor growth in immunodeficient mice. *Nature* 2007;445:106–10.
- Goldstein AS, Huang J, Guo C, Garraway IP, Witte ON. Identification of a cell of origin for human prostate cancer. *Science* 2010;329:568–71.
- Taylor RA, Toivanen R, Frydenberg M, Pedersen J, Harewood L, Australian Prostate Cancer B, et al. Human epithelial basal cells are cells of origin of prostate cancer, independent of CD133 status. *Stem Cells* 2012;30:1087–96.
- Domingo-Domenech J, Vidal SJ, Rodriguez-Bravo V, Castillo-Martin M, Quinn SA, Rodriguez-Barrueco R, et al. Suppression of acquired docetaxel resistance in prostate cancer through depletion of notch- and hedgehog-dependent tumor-initiating cells. *Cancer Cell* 2012;22:373–88.
- Quintana E, Shackleton M, Sabel MS, Fullen DR, Johnson TM, Morrison SJ. Efficient tumour formation by single human melanoma cells. *Nature* 2008;456:593–8.
- Boiko AD, Razorenova OV, van de Rijn M, Swetter SM, Johnson DL, et al. Human melanoma-initiating cells express neural crest nerve growth factor receptor CD271. *Nature* 2010;466:133–7.
- Kelly PN, Dakic A, Adams JM, Nutt SL, Strasser A. Tumor growth need not be driven by rare cancer stem cells. *Science* 2007;317:337.
- Vermeulen L, De Sousa E, Melo F, van der Heijden M, Cameron K, de Jong JH, Borovski T, et al. Wnt activity defines colon cancer stem cells and is regulated by the microenvironment. *Nat Cell Biol* 2010;12:468–76.
- Liu J, Pascal LE, Isharwal S, Metzger D, Ramos Garcia R, Pilch J, et al. Regenerated luminal epithelial cells are derived from preexisting luminal epithelial cells in adult mouse prostate. *Mol Endocrinol* 2011;25:1849–57.
- Chen J, Li Y, Yu TS, McKay RM, Burns DK, Kernie SG, et al. A restricted cell population propagates glioblastoma growth after chemotherapy. *Nature* 2012;488:522–6.
- Schepers AG, Snippert HJ, Stange DE, van den Born M, van Es JH, van de Wetering M, et al. Lineage tracing reveals Lgr5+ stem cell activity in mouse intestinal adenomas. *Science* 2012;337:730–5.
- Driessens G, Beck B, Caauwe A, Simons BD, Blanpain C. Defining the mode of tumour growth by clonal analysis. *Nature* 2012;488:527–30.
- Wang X, Kruihof-de Julio M, Economides KD, Walker D, Yu H, Halili MV, et al. A luminal epithelial stem cell that is a cell of origin for prostate cancer. *Nature* 2009;461:495–500.
- Wang ZA, Mitrofanova A, Bergren SK, Abate-Shen C, Cardiff RD, Califano A, et al. Lineage analysis of basal epithelial cells reveals their unexpected

- plasticity and supports a cell-of-origin model for prostate cancer heterogeneity. *Nat Cell Biol* 2013;15:274–83.
23. Choi N, Zhang B, Zhang L, Ittmann M, Xin L. Adult murine prostate basal and luminal cells are self-sustained lineages that can both serve as targets for prostate cancer initiation. *Cancer Cell* 2012;21:253–65.
 24. Kemp R, Ireland H, Clayton E, Houghton C, Howard L, Winton DJ. Elimination of background recombination: somatic induction of Cre by combined transcriptional regulation and hormone binding affinity. *Nucleic Acids Res* 2004;32:e92.
 25. Heffner CS, Herbert Pratt C, Babiuk RP, Sharma Y, Rockwood SF, Donahue LR, et al. Supporting conditional mouse mutagenesis with a comprehensive cre characterization resource. *Nat Commun* 2012;3:1218.
 26. Schmidt-Supprian M, Rajewsky K. Vagaries of conditional gene targeting. *Nat Immunol* 2007;8:665–8.
 27. Liu S, Cong Y, Wang D, Sun Y, Deng L, Liu Y, et al. Breast cancer stem cells transition between epithelial and mesenchymal states reflective of their normal counterparts. *Stem Cell Reports* 2013;2:78–91.
 28. Gupta PB, Fillmore CM, Jiang G, Shapira SD, Tao K, Kuperwasser C, et al. Stochastic state transitions give rise to phenotypic equilibrium in populations of cancer cells. *Cell* 2011;146:633–44.
 29. Roesch A, Fukunaga-Kalabis M, Schmidt EC, Zabierowski SE, Brafford PA, Vultur A, et al. A temporarily distinct subpopulation of slow-cycling melanoma cells is required for continuous tumor growth. *Cell* 2010;141:583–94.
 30. Hendrix MJ, Sefror EA, Hess AR, Sefror RE. Molecular plasticity of human melanoma cells. *Oncogene* 2003;22:3070–5.