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Chromosome copy number variation in telomerized human bone marrow stromal cells; insights for monitoring safe ex-vivo expansion of adult stem cells

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A B S T R A C T
Adult human bone marrow stromal cells (hBMSC) cultured for cell therapy require evaluation of potency and stability for safe use. Chromosomal aberrations upsetting genomic integrity in such cells have been contrastingly described as “Limited” or “Significant”. Previously reported stepwise acquisition of a spontaneous neoplastic phenotype during three-year continuous culture of telomerized cells (hBMSC-TERT20) didn’t alter a diploid karyotype measured by spectral karyotype analysis (SKY). Such screening may not adequately monitor abnormal and potentially tumorigenic hBMSC in clinical scenarios. We here used array comparative genomic hybridization (aCGH) to more stringently compare non-tumorigenic parental hBMSC-TERT strains with their tumorigenic subcloned populations. Confirmation of a known chromosome 9p21 microdeletion at locus CDKN2A/B, showed it also impinged upon the adjacent MTAP gene. Compared to reference diploid human fibroblast genomic DNA, the non-tumorigenic hBMSC-TERT4 cells had a copy number variation (CNV) in at least 14 independent loci. The pre-tumorigenic hBMSC-TERT20 cell strain had further CNV including 1q44 gain enhancing expression and 11q13.1 loss downregulating MUS81 expression. Bioinformatic analysis of gene products reflecting 11p15.5 CNV gain in tumorigenic hBMSC-TERT20 cells highlighted networks implicated in tumorigenic progression involving cell cycle control and mis-match repair. We provide novel biomarkers for prospective risk assessment of expanded stem cell cultures.

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1. Introduction

Successful trials showing autologous stem cell subpopulations isolated from human adult bone marrow tissue can be grown ex vivo and subsequently reintroduced into patients to improve regenerative repair of large bone defects (Quarto et al., 2001) have prompted need for standardized protocols to broaden the therapeutic scope (Panchalingam et al., 2015). Associated with optimal cell sourcing approaches and cell dosage requirements, the monitoring of procedural risk is of fundamental concern. Cultured cells are susceptible to stochastic acquisition of hereditable changes that may subvert function or introduce a detrimental outcome. Oncogenic changes can be monitored with very sensitive specific techniques, yet the wide diversity of potential aberrations can confound analysis and suitable biomarkers in the context of expanded “hBMSC” populations have yet to be defined. Significant oncogenic changes can range from discrete single codon mutations, gene amplification, loss of tumor suppressor gene function and epigenetic modifications. Since such changes usually reflect or evoke chromosome abnormalities, it was reasonable to propose that karyotypic analysis might suffice to provide an overview of whether the expanded stem cells are fit for therapeutic use (Saito et al., 2011), although this view has raised controversy (Ferreira et al., 2012). As a model system exemplifying accumulated genetic instability in long-term continuously expanded cell cultures, we previously reported that telomerized human bone marrow stromal cell strains hBMSC-TERT (aka “hMSC-TERT”), ordinarily forming heterotopic bone when transplanted with osteoconductive scaffold into immune deficient mice...
(Simonsen et al., 2002), could eventually spontaneously evolve a neoplastic phenotype (Serakinci et al., 2004). Notably, however, the tumorigenic cells retained a normal diploid karyotype (Burns et al., 2008). To improve detection of cytogenetic changes in cultured cells, we hereby describe use of array comparative genomic hybridization (aCGH) to identify segments of the genome existing as different copy number variants (CNV). A reference human diploid fibroblast genomic DNA was compared to bone-forming hBMSC-TERT4 and hBMSC-TERT20 cell strains, versus six sub-cloned tumorigenic cell lines derived from the extended culture neoplastic hBMSC-TERT20 strain of high population doubling level (PDL) (Burns et al., 2005). Inclusion of single-cell derived clones in our comparative analysis was advantageous, since aCGH may fail to detect low-level mosaicism (≤10%) among a heterogeneous cell strain (Elliott et al., 2010). Use of a progressive cell model with comprehensively measured growth kinetics in closely matched cell strains allowed verification of CNV reproducibility. The capacity to correlate genetic aberrations with population doubling level and acquisition of a tumorigenic phenotype, helped identify specific CNV more likely to harbour potentially causative genetic changes. Furthermore, prior cytogenetic information for cancer and differentiation pathway proteins in hBMSC-TERT20 populations provided a verified context for exploring potential relevance of CNV-associated genes. A biological database search tool for interacting genes/proteins confirmed that many CNV-specific genes were highly germane for tumorigenic progression, sharing relevance with events prevalent in human cancers and sarcomas.

2. Materials and methods

2.1. Cell culture

From concern that broad casual use of the term MSC can introduce confusion (Robey, 2017; Caplan, 2017) cells called “hMSC-TERT” in our prior publications are here renamed hBMSC-TERT. The hBMSC strain were cultured from a healthy male donor, 46, XY (age 33) transduced at population doubling level (PDL) 12 with a retroviral vector overexpressing the human telomerase reverse transcriptase gene (hBMSC-TERT cells) was used to derive the hBMSC-TERT2, hBMSC-TERT4 and hBMSC-TERT20 populations. Notably, the hTERT vector wasn’t tagged with an independent co-selectable marker, thus selection relied purely on hTERT function driving growth beyond the senescence observed in untransduced control primary hBMSC. As previously described (Abdallah et al., 2005), eight passages after retroviral transduction (PDL 23), cells were partitioned into two passage regimes, with split ratios of 1:2 or 1:4 to generate hBMSC-TERT2 or hBMSC-TERT4 populations. By PDL 47, hBMSC-TERT4 cells were further partitioned into a 1:20 split ratio hBMSC-TERT20 population. Cell number was calculated for each weekly passage. Prior analysis of neoplasia detected loss of the p16INK4A/ARF locus in both hBMSC-TERT4 and hBMSC-TERT20 populations, plus Kras Q61H mutation specified to hBMSC-TERT20 cells, plus Kras Q61H mutation specific to hBMSC-TERT4 cells and oncogene methylation of the DBCCR1/DBC1/BRINP1 promoter specific to hBMSC-TERT20 cells (Serakinci et al., 2004). At late passage (PDL 440), hBMSC-TERT20 was used to derive single-cell sub-clones designated -βB3, -B8C, -B6D, -BD1, CE8 and DB9 as described (Burns et al., 2005). Subsequent histological analysis of hBMSC-TERT20 strains and subclones examined a panel of cancer pathway prognostic biomarker (Burns et al., 2008). All cells were grown in phenol red-free minimal essential medium (MEM) supplemented with 10% batch-tested fetal bovine serum (FBS) and 1% penicillin/streptomycin (Gibco Invitrogen) and maintained in a 5% CO2 humidified incubator at 37 °C.

2.2. Array-based Comparative Genomic Hybridization (aCGH)

Genomic DNA was prepared using the Puregene DNA Purification Kit (Qiagen). aCGH was performed following the standard Agilent protocol (V6.1). Briefly, 700 ng of hBMSC-TERT lineage cell genomic DNA and 700 ng of reference diploid human fibroblast genomic DNA 46.XX was digested with Alul and RsaI and labeled with Cy5- or Cy3-dUTP (Agilent). Following purification with Microcon YM-30 filters (Millipore), the labeled DNA yield and quality was checked on a NanoDrop ND-1000 UV-VIS Spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA) and Agilent 2100 Bioanalyzer using Bioanalyzer DNA High Sensitivity (Agilent Technologies). The labeled samples were hybridized at 65 °C on Agilent dual colour arrays (Sureprint G3, 2x400k cat.#G4825A; Agilent Technologies) for 24 h in a rotator oven at 20 rpm. The annotation files corresponded to NCBI build 36.1 of the human genome hg18 (March 2006) containing 411,056 60-mer probes. The comprehensive probe coverage allowed genome-wide DNA CNV profiling focused on known genes, promoters, miRNAs, pseudoautosomal and telomeric regions. Slides were washed according to the protocol and scanned immediately at 2 μm resolution on an Agilent G2565CA high-resolution scanner. Data was extracted using Agilent Feature Extraction software and the resulting files were processed with the Bioconductor limma package version 2.18.2, with the raw data cleaned for background noise using the normexp convolution model. The resulting signal was processed using a quantities-based normalization procedure. Figures were generated with help of R software ggplot2 implementation of the Grammar of Graphics.

2.3. RT-PCR Analysis of gene expression

Cellular RNA from hBMSC-TERT4 PDL-175 and hBMSC-TERT20 PDL-337 was isolated using a single-step method with TRIzol (Invitrogen, Taastrup, Denmark) according to manufacturer’s instructions. First-strand complementary cDNA was synthesized from 4 μg of total RNA in accordance to a Revertaid H minus first-strand cDNA synthesis kit (Fermentas). Real-time polymerase chain reaction (RT-PCR) utilized the StepOne PlusTM RT-PCR system (Applied Biosystems) with double-strand DNA-specific SYBR — Green I luminescent dye. In a total reaction volume of 10 μL, 20 pmol/mL of each primer (DNA Technology A/S or Eurofins, Ebersberg, Germany) and 10 pmol/mL for each reference gene was used with Fast SYBR® Green master mix (ABI). The cycle conditions included an initial denaturation step at 95 °C for 20 s and 40 cycles of 95 °C for 3 s, and 60 °C for 30 s. Normalization was achieved via the reference gene β2-microglobulin (Lupberger et al., 2002) (primer sequences in Supplementary Table 1).

In vivo xenograft of hBMSC-TERT in immuno-deficient mice hBMSC-TERT4 PDL 192 cells (5 × 10^6) combined with hydroxyl-apatite/tricalcium phosphate 1–2 mm diameter granules (HA/TCP, 40 mg, Zimmer Scandinavia, Denmark) were transplanted subcutaneously into the dorsum of 8-week- old female NOD/SCID mice (NOD/LtSz-Pkrdcsidc) as described (Burns et al., 2010). The transplants were recovered eight weeks after transplantation, transferred to 4% neutral buffered formalin for about 45 min, and then formic acid was added for 2 days. Adopting standard histopathologic methods, the HA/TCP implants were embedded in paraffin and 4-μm tissue sections were stained with hematoxylin and eosin Y (H&E) (Bie & Berentsen Reagenslaboratorium). Similarly, tumorigenic hBMSC-TERT20 PDL 480 cells (5 × 10^6) combined with Matrigel™ were transplanted subcutaneously into the murine dorsal region and recovered two weeks after transplantation, fixed in 4% neutral buffered formalin as above and embedded in paraffin for subsequent H&E staining of 4-μm tissue sections.

2.4. Bioinformatic characterization of copy number variable genes

To explore CNV relevance to known hBMSC-TERT cell biology, we referenced prior molecular studies of tumorigenic events, including genetic abnormalities and the expression of proteins involved in pathways to cancer, the cell cycle, DNA mismatch repair and ossification. Associations between such hBMSC-TERT qualified molecules and CNVs were made using the Search Tool for Retrieval of Interacting Genes/Proteins database (STRING, version 10.0), a database comprised known and predicted interactions, including direct (physical) and indirect (functional)
associations based on genomic context, high throughput experiments, conserved co-expression and previous knowledge (Szklarczyk et al., 2015). In the first instance, we mapped CNV associated with experimentally known hBMSC-TERT pathways in cancer. Subsequently, to confirm the significance of CNV specific to preneoplastic hBMSC-TERT20 cells, software-derived high confidence 1st shell network interactors to SMYD3 (SET and MYND domain-containing protein 3) and SIRT1 (Sir22ucin 1) were used to map further CNV target associations in epigenetic pathways. Software clustering tools included KEGG pathway enrichment (Kanehisa et al., 2016).

2.5. Statistical analysis

For the real-time PCR analysis, a two-tailed t-test was applied to analyze the expression of the CNV target genes in different hBMSC-TERT cell populations. Fold-changes in gene expression between samples with p values < 0.05 were considered significant. The STRING v10 database clustering coefficient for interactions assumed a statistical background of the whole genome.

3. Results

3.1. Cell growth kinetics; passage split ratio associated tumorigenicity

As reported, the subculture passage split ratio was an extrinsic factor that influenced hBMSC-TERT cell growth rates and led to three passage split ratio-specific growth curves (Fig. 1A). hBMSC-TERT20 cells, passed 1:20, showed the greatest step-wise acceleration in growth rate, leading to a consistent DT of only 1.4 days by PDL-256, the point in their evolution when xenografts were tumorigenic. Propagated with a 1:4 passage split ratio, hBMSC-TERT4 cells evolved doubling time changes during passage from 4.6 days at PDL-74, to 4.2 days at PDL-95 and 1.5 days at PDL-169. The higher 1:4 seeding density for hBMSC-TERT4 influenced culture contact inhibition (Abercrombie, 1970) since cells were promptly in contact with each other after just one division. In contrast, even 24 h after seeding, 1:20 split hBMSC-TERT20 cells were distributed more autonomously on the culture surface. Previously detected genetic and epigenetic aberrations discovered in the hBMSC-TERT strains included a Kras Q61H oncogene activation detected in hBMSC-TERT4 cells at PDL-169. At the time, we reported that hBMSC-TERT4 cells at PDL-169 were nevertheless not tumorigenic. Confirming this was indeed the case, PDL 192 hBMSC-TERT4 cells subcutaneously transplanted with osteoconductive scaffold, formed a trabecular bone matrix tissue after 8 weeks in immune compromised mice, n = 4/4 (Fig. 1B). Thus, we were confident of comparing non-tumorigenic (hBMSC-TERT4 and early hBMSC-TERT20 populations) versus tumorigenic phenotypes (high PDL hBMSC-TERT20 subclones) when interpreting the CNV observations.

3.2. Genetic aberrations confirmed and discovered by array CGH

To generate array CGH profiles, glass slide anchored probes of known mapped sequences representing homogeneous regions in the genome, competitively bound two samples of “reference” versus “test” genomic DNA, each labeled with differentiating fluorescent dyes. Consequently, copy number could be indirectly calculated from a ratio...
of fluorochrome intensities proportional to the relative probe-spanning chromosome abundance of the samples. Profiles for each chromosome comprised a ranking of log2 fluorescent ratios plotted according to the probe’s corresponding physical position on the genome. The plotted data were normalized with a median set to log2(ratio) = 0 for regions of no change; positive means represented duplicated whilst negative means represented deleted regions in the test genome. Since results were based on fluorescent measurement, the signal was plotted as continuous even if the underlying biological process was discrete (relative copy numbers of DNA sequence). N.B. The relative copy number value in the test sample could vary due to heterogeneous incidence in the cell population. For confidence, aberrations with a minimum of four probes in the region were chosen. One exception, at 11q13.1 had an individual probe with a particularly strong signal reproduced in most test samples. With very characteristic profile patterns, the hBMSC-TERT strains and isogenic expanded subclones confirmed the very high reproducibility of the aCGH approach. Microdeletions in chromosome regions 1q21.1, 2q11.2, 2q21.1, 3q26.1, 9p21.3, 11p15.1, 15q24.2, 17q23.2, 21q11.2 and 22q11.23 were ubiquitous in both hBMSC-TERT substrains and all subclones. The known p16INK4a/ARF microdeletion at 9p21.3, one of the clearest aberrations found (Fig. 2A), was now better defined by 30 consecutive probes spanning the CDKN2A, CDKN2B and adjacent MTAP loci (Fig. 2B). The CNV profile indicated the span of chromosome loss was the same for hBMSC-TERT4, hBMSC-TERT20 and all the hBMSC-TERT20 subclones. The 9p21.3 CNV seen in hBMSC-TERT4 had a probe deletion ratio range (−1 to −3) that was substituted by a narrower range of larger ratios (−2 to −3) in hBMSC-TERT20 cells and subclones, likely indicative of accrued missing genomic segments. For the non-ubiquitous CNV, restricted to more specific cell populations, there was a tendency for the CNV ratio between sample and control to be 1.

To more closely correlate CNV to the tumorigenic phenotype, we focused on CNV specific to the hBMSC-TERT20 strain and its tumorigenic subclones (Table 1). Notably, two CNV absent in non-tumorigenic hBMSC-TERT4 PDL 88 cells were found in the pre-tumorigenic hBMSC-TERT20 PDL116 population and subsequent hBMSC-TERT20 PDL440 derived tumorigenic subclones; namely, a 1q44 gain (Fig. 3A) and a microdeletion at 11q13.1 (Fig. 3B). The region concerning CNV 1q44 co-involved two probes targeting SMYD3 that encodes a histone methyltransferase involved in the proliferation of cancer cells (Hamamoto et al., 2004). The region lost by CNV 11q13.1 co-involved MUS81, a crossover junction endonuclease. RT-PCR analysis of gene expression in hBMSC-TERT4 PDL 175 versus hBMSC-TERT20 PDL 337 confirmed that changes in relative expression agreed with expectations from the corresponding CNV type. This was not the case for a more centromeric chromosome 11 control gene MAP3K11 outside the CNV region (Fig. 3C). The chromosome showing most imbalances and CNV was chromosome 11. Specific to all tumorigenic hBMSC-TERT20 subclones we observed amplification of the short (p) arm of chromosome 11 at the telomeric region 11p15.5 (chr11:0–570,000) (Fig. 4A) comprising 37 genes from IFTIM5 to PHRF1 including HRAS (Fig. 4B). This region didn’t involve a centromerically distal neighboring cluster of imprinted
genes associated with Beckwith-Wiedemann syndrome (BWS) and a high risk of development of childhood sarcomas. Nonetheless, the BWS region may remain relevant for sub-clone—CE8, since the CNV log2 ratio for this particular clone was consistently 0.5 higher than the other sub-clones, indicative of a full chromosome 11 imbalance. Our analysis restricting the 11p15.5 amplified region window to chr11:0–1000000 to comprise at least a further 32 influenced genes (Fig. 4C), was most likely a conservative estimate for hBMSC-TERT20-CE8.

3.3. Interacting Genes/Proteins suggest a CNV role in tumorigenesis

Tumorigenic events characterized from previous studies exploring events in hBMSC-TERT20 cell tumorigenic progression (Serakinci et al., 2004) (Burns et al., 2005) (Burns et al., 2008), provided a contextual framework for exploring CNV relevance. The principle aspects of the contextual framework could be described as follows: Driving hBMSC-TERT characteristics, hTERT associated with many genes and proteins belonging to KEGG pathways in cancer, including cell cycle regulators; TERT characteristics, hTERT associated with many genes and proteins framework for exploring CNV relevance. The principle aspects of the product p21Cip1, the CDKN1B product p27Kip1, CCND1 derived Cyclin events in hBMSC-TERT20 cell tumorigenic progression (Serakinci et al., 2004) (Burns et al., 2005) (Burns et al., 2008), was most likely a conservative estimate for hBMSC-TERT20-CE8.

Table 1

<table>
<thead>
<tr>
<th>Cytoband locus</th>
<th>Copy number variation (CNV)</th>
<th>CNV size (kbp)</th>
<th>hBMSC-TERT4 PDL 88</th>
<th>hBMSC-TERT20 PDL 116</th>
<th>hBMSC-TERT20 BB3</th>
<th>hBMSC-TERT20 BC8</th>
<th>hBMSC-TERT20 BD6</th>
<th>hBMSC-TERT20 BD11</th>
<th>hBMSC-TERT20 CE8</th>
<th>hBMSC-TERT20 DB9</th>
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<td>+</td>
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<tr>
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<td>+</td>
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<td>+</td>
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* (a) chr1:65,375,000–65,390,000 (b) chr1:65,550,000–65,620,000.

had an overall clustering coefficient of 0.794 and more interactions than would be predicted from chance, indicating the CNV were likely to be biologically connected to tumorigenic events found in hBMSC-TERT20 cells. As many as twenty CNV-specific interactors recruited in this network were from the 23 STRING identified proteins within the 11p15.5 CNV chromosome gain locus, including a cluster of genes encoding interferon-induced transmembrane protein family members. In contrast, for the ubiquitous 1q21.1 CNV loss that also harbored 37 Refseq coding sequences, including non-annotated genes, only six were identified by the STRING database of which just two, PPIL4C and NBP110, interacted with the network. A KEGG pathway analysis of the network indicated that ten of the a priori defined contextual network proteins (CCND1, CDKN1A, CDKN1B, COL1A1, COL4A1, EGFR, IBSP, LAMA1, TP53, VEGFA) were components of the PI3K/AKT/mTOR signaling network important for regulating the cell cycle. Notably, four hypothetical hBMSC-TERT20 sub-clones (AP2A2, PSMD13, SIRT3 and HRAS), interacted with this pathway. Moreover, it was possible to derive additional networks more specifically related to SMYD3 (Fig. 6B) and epigenetic signaling (Fig. 6C) (a total of 38 highly predicted functional network partners from a total of 67 STRING identified gene products).

3.4. Evidence for CNV contributions to epigenetic deregulation

The STRING database for the contextual framework above didn’t indicate a direct interaction for the 1q44 CNV gain candidate gene SET and MYND domain-containing protein 3 (SMYD3). Yet its relevance can be predicted, as acetylation of the histone H3 TERT promoter region is predicted, as acetylation of the histone H3 TERT promoter region is one of several targets for this histone methyltransferase (Liu et al., 2007), a principal epigenetic modification of chromatin that can determine gene expression, genomic stability and cell mitosis. Thus, STRING was used to identify 10 highly predicted SMYD3 partners, forming a contextual framework for exploring SMYD3-related CNV relevance. Eight SMYD3 predicted functional network partners directly interacted with 13 predicted proteins from 58 STRING identified target genes spanned by 6 CNV. Notably, the network involved the 9p21.3 CNV genes and most of the highly predicted SMYD3 functional network partners interacted with HRAS from the 11p15.5 CNV (Fig. 6B).

Fig. 3. CNV specific for pre-tumorigenic hBMSC-TERT20 cells and tumorigenic subclones. A, Array CGH profile for 1q44 in each cell type. Axes as described in Fig. 2. Plotted dot size proportional to overall intensity of the probe signal. Chromosome 1 ideogram, red bar highlights the 1q44 – 300 kbp CNV region spanning USCC database annotated genes SMYD3, TFE3M and chromosome 1 open reading frame 71, C1orf71 located within chr1:244,500,000–244,800,000, B, Array CGH profile for 11q13.1 in each cell type. Chromosome 11 ideogram, red bar highlights the 11p13.1–15 kbp CNV region spanning USCC database annotated genes SNC2, CFLI and MLHS1 within chr11:65,555,000–65,620,000. C, RT-PCR analysis for expression of 1q44 CNV SMYD3 gene, 11q13.1 MLHS1 and a neighboring 11q13.1 gene outside the CNV region, MAP3K11. (*p<0.05). Opposing red arrowheads represent the centromeric region.
The histone NAD dependent protein deacetylase Sir2 (SIRT1) is another epigenetic regulator of telomeric maintenance and highly relevant to cell cycle, DNA repair and apoptosis, linking transcriptional regulation directly to intracellular energetics. Using STRING to identify highly predicted SIRT1 partners resulted in a contextual framework incorporating 19 predicted proteins from 59 STRING identified genes spanned by nine different CNV loci, again including the 9p21.3 CNV targets CDKN2A and CDKN2B that ordinarily inhibit histone acetylation.

**Fig. 4.** CNV specific for hBMSC-TERT20 tumorigenic subclones. A, Array CGH profile for 11p15.5 in each cell type. Axes as described in Fig. 2. Plotted dot size proportional to overall intensity of the probe signal. B, Chromosome 11 ideogram, red bar highlights the 11p15.5 ~ 570 kbp CNV spanning USCC and Refseq database annotated genes including HRAS within chr11:0–570,000. C, Chromosome 11 ideogram, red bar highlights the 11p15.5 ~ 450 kbp CNV specific to clone CE8 cells spanning USCC and Refseq database annotated genes including PIDD, POLR2L and CD151 within chr11:570,000–1000,000. This was a conservative estimate, CE8 CNV indicated whole chromosome 11 imbalance. Opposing red arrowheads represent the centrosomic region.
TERT20 tumorigenicity arose in SKY of clinical grade hBMSC during primary expansion by SKY karyotyping (Stultz et al., 2016). In such contexts, monitoring the genetic stability able phenotypes inducing cell senescence, growth arrest or apoptosis confer an evolutionary growth advantage, i.e. detrimental non-sustain-tization phase may introduce transient genetic errors and karyotypic sources aren’t prone to neoplastic transformation (Roseti et al., 2014) isolation, expansion, manipulation, preclinical evaluation, engraftment consistency, functional efficacy and safety (Furlani et al., 2009). Traditional in vivo tumorigenicty assays can be incompatible with recommendations for minimal cell expansion time frames and prompt patient application to minimise risk of genomic mutations (Wang et al., 2013) (Froelich et al., 2013). Increased need for testing will accompany non-hBMSC cells procured as ATMP from other tissue sources (Sacchetti et al., 2016) and innovative approaches to enhance cell expansion or function, e.g. hypoxic culture conditions can influence chro-mosome stability (Ueyama et al., 2012) (Bigot et al., 2015) (Anderson et al., 2016). Bioprocessing strategies for large-scale production of hBMSC (Panchalingam et al., 2015) will need to meet regulatory authority product characterization requirements (Mendicino et al., 2014). Suitable biomarker panels for improved prompt assessment of tumorigenic risk pre- and post-engraftment (Golding et al., 2011) would be of enormous benefit.

Potential problems in obtaining sufficient mitotic spreads from rela-tively slow-growing primary hBMSC have been largely overcome (Hwang et al., 2013). In most cases, chromosomal G-banding or SKY analysis generally suggested that the karyotype is relatively stable (Chen et al., 2014) and cultured stromal cells from diverse tissue sources aren’t prone to neoplastic transformation (Roseti et al., 2014) (Ruan et al., 2014). Nonetheless, a turbulent initial cell culture acclimation phase may introduce transient genetic errors and karyotypic abnormalities that diminish upon further passage because they fail to confer an evolutionary growth advantage, i.e. detrimental non-sustain-able phenotypes inducing cell senescence, growth arrest or apoptosis (Stultz et al., 2016). In such contexts, monitoring the genetic stability of clinical grade hBMSC during primary expansion by SKY karyotyping may more readily help decide upon suitability for use, even if hBMSC-TERT20 tumorigenicty arose in SKY “normal” diploid cells.

Array CGH is a sensitive approach for detecting cytogenetic abnor-malities, in particular, the Agilent 400 K human array provided genome-wide CNV profiling without need for amplification or complexity reduction with comprehensive probe coverage enhanced by emphasis on known genes, promoters, miRNAs, pseudautosomal and telomeric regions. However, since population variation may lead to CNV in roughly 12% of the human genomic DNA of “healthy” cells, setting safety thresholds is not necessarily straightforward. Since aCGH is a method that relies on unique sequence probe hybridisation it has limitations for the detection of repeat sequences, pseudogenes and insight into the orientation or location of inser-tions, e.g. failing to detect reciprocal translocations. Nonetheless, sensitive detection for intragenic deletions can be obtained among the various arrays available (Askree et al., 2013; Haraksingh et al., 2017).

Defining covert events indicative of tumorigenic predisposition is particularly challenging, given the complexity of cell processes and difficulty in determining the timing of events and their consequences. De-pite improved detection from array CGH, interpretation of the significance of the CNV event may be problematical and clinical rele-vance requires careful interpretation (Hollenbeck et al., 2016) (Savola et al., 2007) (Zhao and Zhao, 2016). To this end the hBMSC-TERT20 model presented several strong points. Independently acquired prior data provided a contextual framework with which to assess CNV. The long-term evolution of the tumorigenic phenotype and contrasting non-tumorigenic closely-matched strains enabled comparisons to identify elusive “pre-neoplastic” events. Verification of CNV persistence in single-cell derived clones provided a test of clonal penetrance and underscored likelihood that the CNV contributed to a persistent prolife-rative growth advantage.

Our three-year hBMSC-TERT cell expansion model monitored cyto-genetic abnormalities and stochastic events leading to tumorigenesis in an isogenic context, providing insights for monitoring ATMP cell cul-tures for tumorigenic risk. Initial suspicion that loss of the Ink4a/ARF locus (CDKN2A) was a microdeletion, detectable using PCR amplifica-tion yet not by FISH (Serakinci et al., 2004) or SKY (Burns et al., 2008), was confirmed. In addition, aCGH indicated the ~151 kbp microdeletion included an exon of MTA3 in addition to CDKN2a and CDKN2b. Such covert 9p21 deletions were responsible for FISH mis-diagnosis in Ewing sarcomas (Savola et al., 2007). Down regulation of MTA3 expression concordant with copy number loss has been highlighted in human tumor samples (Kryukov et al., 2016) and osteosarcomas (Jour et al., 2016), generating a PRMT5 metabolic pathway vulnerability. Higher inci-dence of p16INK4a deletions in cultured cell lines versus primary gli-omas, was attributed to a strong cell culture imposed selective pressure (Hartmann et al., 1999). Indeed, p16INK4a expression has close association with contact inhibition of growth in human embryo lung fibroblasts (Wieser et al., 1998) and hBMSC senescence (Shibata et al., 2007). Nevertheless, beyond the culture environment, p16INK4a marked-inhibility the proliferation of aged pancreatic islet stem cells in vivo (Krishnamurthy et al., 2006). The specific 9p21 CNV loss in hBMSC-TERT4 was reproduced with a stronger signal in hBMSC-TERT20 cells, suggesting elaboration of a pre-existing genetic aberration. This makes it likely that the 9p21 CNV initiated before the hBMSC-TERT cells were distributed as 1:4 and 1:20 split-ratio-specific populations, making this an earlier event than previously described. Of note, the PCR based method used to detect the 9p21 loss had limited sensitivity and mosaicism within a heterogeneous population could allow variant cells to remain undetected (Baker et al., 2016). Translating a cell specific growth advantage to a detectable change in growth rate of the whole population can be delayed in hBMSC cultures (Garcia et al., 2010) quelling expectation that one may simply detect genetic instabil-ity from changes in growth rate kinetics.

Many of the CNV found in all hBMSC-TERT cultures (14/22), might simply reflect a difference pertaining to the comparative refer-ence control DNA, however bioinformatic STRING based interactions indicated that 10 of these ubiquitous CNV contained genes interacting with our hBMSC-TERT20 contextual framework for pathways in cancer. Further interventional experiments beyond the scope of this manuscript would be needed to verify their functional contribution. Focusing, rather, on CNV distributed more heterogeneously among the cell populations, hBMSC-TERT4 cells had one specific 21q11.2 CNV loss, whilst non-tumorigenic hBMSC-TERT20 a 1q44 CNV gain and a 11q13.1 CNV loss that persisted in all the tumorigenic hBMSC-TERT20 subclones. Such a cell strain distribution made the latter two events potential pre-neoplasia biomarkers and notably the 1q44 CNV region harbored the SMYD3 (Set and MYND domain containing protein 3) oncogene (Mazur et al., 2014) whilst the 11q13.1 CNV region harbored the MUS81 (Mus81-Eme1 endonuclease) tumor suppressor gene (McPherson et al., 2004). Consistent with a role in the replication stress response (Minocherhomi et al., 2015) and ultrasonasensitivity to its expression change (Yu et al., 2008), down-regulation of cross-over junction endonuclease MUS81 was a prognostic biomarker for colorectal carcinoma (Wu et al., 2011).
CNV events don’t necessarily change gene expression (Kuijjer et al., 2012), thus it was reassuring to verify concordant SMYD3 and MUS81 expression changes by gene expression analysis to confirm their potential significance. SMYD3 in particular has been shown to be a transcriptional potentiator of multiple cancer promoting genes in liver and colon cancer development (Sarris et al., 2016) with potential to promote the cell cycle (Tsai et al., 2016). Outcomes of increased SMYD3 expression in cultured cells include reduced contact inhibition and accelerated growth (Luo et al., 2009) (Ren et al., 2011). KEGG analysis of our contextual framework network indicated components of the PI3K/AKT/mTOR signaling network and SMYD3 has been shown to be critical for activation of AKT1 (Yoshioka et al., 2016). Moreover, upregulation of SMYD3 in bladder cancer can promote cancer progression and activate autophagy (Shen et al., 2016), rendering cancer cells resistant to starvation (Galluzzi et al., 2015), a phenotype highlighted in hBMSC-TERT20 subclones (Burns et al., 2011). Though prevalent in cancers, a role for SMYD3 in sarcomas has yet to be reported, however p53-mutant mice only haploinsufficient for MUS81 were already predisposed to develop sarcomas (Pamidi et al., 2007).

The 11p15.5 CNV gain, closely correlated with hBMSC-TERT strain tumorigenicity, contributed the largest number of potential interactors in our context-defined cancer pathways network. Curiously, despite more extensive full chromosome 11 imbalance, hBMSC-TERT20-CE8 tumors arose latently compared to those for the other clones (Burns et al., 2011).
2008). Conspicuous among the many genes affected by the 570 kbp 11p15.5 CNV gain, HRAS (Hras proto-oncogene, GTPase) was activated in gliomas by copy number gains more frequently than by activating mutations (Jeukens et al., 2007). Ras activity has context-dependent outcomes, critically dependent on the pre-existing telomerase and CDKN2A encoded p16INK4a status of the cells. Though HRAS overexpression can induce premature senescence in primary human cells, in clonalogenic keratinocytes from the stem cell compartment it could evoke tumorigenic progression (Maurelli et al., 2016). It may seem counterintuitive that hBMSC-TERT4 cells bearing a KRAS G61H activation didn’t form tumors, however, the outcome of KRAS oncogene expression is highly dependent on cellular context (Guerra et al., 2003) and KRAS mutations prove selective only if they occur in cells with an appropriately abrogated defense mechanism (Lee and Bae, 2016). Moreover, the status of the wild-type HRAS isoform continues to influence mutant KRAS driven signaling (Bentley et al., 2013) and tumorigenic susceptibility may require KRAS copy number gains in addition to mutation (Kerr et al., 2016). The hBMSC-TERT4 phenotype was consistent with recent observations that over-activation of kras in immature murine osteoprogenitor cells increased the number of descendant osteoblasts (Papaianniou et al., 2016).

How relevant is the hBMSC-TERT model for guiding ATMP safety? The “extracurricular” additional activities of ectopic hTERT (Cong and Shay, 2008) may not only prevent aneuploidy but also introduce an artefactual bias subverting corrective responses. Extrapolating our results to primary cultures, needs consideration that hBMSC-TERT cells may have an enhanced innate tumorigenic risk. Wayward primary hBMSC may be more readily be detected through karyotypic abnormalities and show growth arrest, senescence or apoptosis as appropriate checkpoint responses that limit tumorigenic risk. Moreover, the time taken for neoplastic evolution in hBMSC-TERT20 cells was well beyond typically contemplated ATMP culture periods (Lechanteur et al., 2016).

The hBMSC-TERT20 neoplastic model nonetheless proved that di rectly accrued genetic change in cultured cells could not only accelerate growth rate, but also drive neoplasia. With authentic tumorigenesis, the hBMSC-TERT20 model has greatest value in revealing relatively covert yet significant abnormalities that might ordinarily pass undetected in short-term cultures. A rare example of spontaneous tumorigenesis from primary cultured hBMSC verified by STR profiling supports concern for monitoring (Pan et al., 2014), yet even with a “three strikes you’re out” model (Vogelstein and Kinzler, 2015), tumorigenesis need not be an inevitable outcome. Even with at least three neoplastic contributors, hTERT expression, the 9p21 microdeletion spanning three checkpoint genes and Kras G61H activation, subsequently grown hBMSC-TERT4 cells still formed quality good bone tissue upon experimental implantation. Revisiting our well-characterized neoplastic model with aCGH highlighted extra discriminating events in the tumorigenic hBMSC-TERT20 cells, exposed limitations of variously proposed monitoring methods and provided further insights into culture-derived neoplasia. Bioinformatic analysis of CNV locus genes provided strong supportive evidence that chromosomal changes in the diploid cells contributed to pathways engaging co-existent genetic aberrations to establish tumorigenic progression. The model provides a richly annotated experimental framework for future interventional studies verifying the critical pathways driving neoplasia arisen in stem cells.

The hBMSC-TERT model can guide rational design for improved predictive genomics (Wang et al., 2015) by introducing novel biomarkers of neoplastic risk for tailored cost-effective arrays with enhanced probe coverage dedicated to safe stem cell expansion (Pan et al., 2014) and complementary platforms for epigenetic monitoring (Wagner et al., 2016). Our direct experimental evidence that mutation of stem cells with conversion of extrinsic factors can altogether create conditions to drive tumorigenesis agrees with what has been learned from mapping cancer risk in vivo (Zhu et al., 2016; Sheffield et al., 2017).

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Disclosure of potential conflicts of interest

The authors declare no potential conflict of interest.

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