Modulation of junction tension by tumor suppressors and proto-oncogenes regulates cell-cell contacts

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RESEARCH ARTICLE

Modulation of junction tension by tumor suppressors and proto-oncogenes regulates cell-cell contacts

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ABSTRACT

Tumor suppressors and proto-oncogenes play crucial roles in tissue proliferation. Furthermore, de-regulation of their functions is deleterious to tissue architecture and can result in the sorting of somatic rounded clones minimizing their contact with surrounding wild-type (wt) cells. Defects in the shape of somatic clones correlate with defects in proliferation, cell affinity, cell-cell adhesion, oriented cell division and cortical contractility. Combining genetics, live-imaging, laser ablation and computer simulations, we aim to analyze whether distinct or similar mechanisms can account for the common role of tumor suppressors and proto-oncogenes in cell-cell contact regulation. In *Drosophila* epithelia, the tumor suppressors Fat (Ft) and Dachsous (Ds) regulate cell proliferation, tissue morphogenesis, planar cell polarity and junction tension. By analyzing the evolution over time of *ft* mutant cells and clones, we show that *ft* clones reduce their cell-cell contacts with the surrounding wt tissue in the absence of concomitant cell divisions and over-proliferation. This contact reduction depends on opposed changes of junction tensions in the clone bulk and its boundary with neighboring wt tissue. More generally, either clone bulk or boundary junction tension is modulated by the activation of Yorkie, Myc and Ras, yielding similar contact reductions with wt cells. Together, our data highlight mechanical roles for proto-oncogene and tumor suppressor pathways in cell-cell interactions.

KEY WORDS: Fat/Dachsous and Hippo pathways, Myc, Ras, Junction tension, Myosins, Clone shape

INTRODUCTION

Tumor suppressors and oncogenes play fundamental functions in cell proliferation, growth and apoptosis. The analyses of these functions have led to important advances in our understanding of tissue development and homeostasis as well as pathologies, including tumorigenesis (for reviews, see Zhao et al., 2011; Patel and Edgar, 2014; Baillon and Basler, 2014). In *Drosophila*, analysis of the sizes and shapes of somatic clones affecting tumor suppressor and proto-oncogene activities is instrumental to understanding their contribution in tissue morphogenesis, organization and homeostasis (Resino et al., 2002; Baena-Lopez et al., 2005; Mao et al., 2011; Wartlick et al., 2011; Kuchen et al., 2012; Worley et al., 2013; Restrepo et al., 2014; Heemskerk et al., 2014). Accordingly, somatic mutant clones are essential for unveiling how tumor suppressor and proto-oncogene activities modulate tissue proliferation, growth, cell-cell interactions and cell competition (for a review, see Wagstaff et al., 2013). In particular, the functions of tumor suppressors and proto-oncogenes in tissue organization and morphogenesis have often been recognized as their respective loss and gain of function leads to the formation of a rounded group of mutant cells (somatic clones) having a smooth boundary with the surrounding wild-type (wt) cells and thus reducing their contacts with neighboring wt tissue (Justice et al., 1995; Prober and Edgar, 2000, 2002; Baena-Lopez et al., 2005; Mao et al., 2006; Worley et al., 2013). This property is shared by the Ras and Myc proto-oncogenes as well as components of the Fat/Dachsous (Ft/Ds) and Hippo pathways (Justice et al., 1995; Adler et al., 1998; Johnston et al., 1999; Prober and Edgar, 2000, 2002; Garoia et al., 2000; Baena-Lopez et al., 2005; Mao et al., 2011; Worley et al., 2013).

Experimental and modeling approaches converged to show that the cell-cell contacts between two cell populations can be modulated by cell-cell adhesion, cell cortical contractility and cell division rate and orientation; in particular, the analysis of tissue or compartment boundary formation has provided important insights into the mechanisms modulating cell-cell contacts between two cell populations in response to cell signaling (for a review, see Fagotto et al., 2013). An increase in cell junction tension (which is larger when cortical contractility increases or adhesion decreases) at the interface between two tissues is known to favor a straight boundary between these two tissues or two compartments within a tissue and is essential for tissue development (Graner, 1993; Brodland, 2002; Käfer et al., 2007; Krieg et al., 2008; Hilgenfeldt et al., 2008; Landsberg et al., 2009; Monier et al., 2010; Aliee et al., 2012; Röper, 2012; Fagotto et al., 2013; Calzolari et al., 2014; Umetsu et al., 2014). Theoretical analysis shows that randomly oriented cell divisions induce diffusive random cell displacements (Ranft et al., 2010), thereby adding a slight amount of disorder between two cell populations (Block et al., 2007; Radszuweit et al., 2009). Experimental analyses of cell division rate and orientation demonstrated that an increase in cell junction tension is necessary to prevent disorder introduced by cell divisions occurring near the anterior-posterior parasegment boundary of the *Drosophila* embryo (Monier et al., 2010). Although the role of cell division rate at the *Drosophila* dorsal-ventral boundary of the wing imaginal disc remains a matter of debate, cell division orientation has been shown to contribute to its shaping (Aliee et al., 2012). Cell divisions oriented perpendicular to the boundary can increase the number of cell junctions at the boundary, and hence its raggedness, whereas cell divisions parallel to the boundary can decrease its raggedness. Notably, these effects of cell divisions can be reinforced or conversely weakened according to the number and orientation of cell rearrangements following the divisions.

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We initially aimed to understand how Ft/Ds pathway, which modulates the activity of the myosin Dachs and of the Hippo/Yorkie pathway, promotes somatic clone rounding (Mao et al., 2006, 2011; Cho et al., 2006). The tumor suppressors Ft and Ds encode large proto-cadherins that interact in a heterophilic manner and regulate proliferation via the Hippo/Yki pathway or mitochondrial metabolism, planar cell polarity and tissue morphogenesis by promoting oriented cell divisions and cell-cell rearrangements (Mahoney et al., 1991; Clark et al., 1995; Matakatsu and Blair, 2004; Baena-Lopez et al., 2005; Cho et al., 2006; Silva et al., 2006; Willecke et al., 2006; Harvey and Tapon, 2007; Mao et al., 2011; Donoughe and DiNardo, 2011; Bosveld et al., 2012; Brittle et al., 2012; Marcinkevicius and Zallen, 2013; Lawrence and Casal, 2013; Matis and Axelrod, 2013; Degoutin et al., 2013; Sing et al., 2014). Within tissues, opposing gradients of Ds and the Golgi resident kinase Four-jointed, which regulates Ft-Ds interaction, result in the planar polarization of Ft and Ds (Ishikawa et al., 2008; Brittle et al., 2010, 2012; Simon et al., 2010; Bosveld et al., 2012; Ambegaonkar et al., 2012). One of the effectors of Ft and Ds planar polarization is Dachs, which regulates cell division orientation, cell rearrangements, cell affinity, proliferation rate and junction tension (Mao et al., 2006, 2011; Bosveld et al., 2012; Brittle et al., 2012). Dachs membrane localization is promoted by the DHHC palmitoyltransferase Approximated (Matakatsu and Blair, 2008), and is inhibited by the interaction of the F-Box ubiquitin ligase FbxL7 with Ft (Rodrigues-Campos and Thompson, 2014; Bosch et al., 2014). Conversely, the Ds intracellular domain can form a complex with Dachs *in vitro* and Dachs is proposed to be planar polarized in response to Ds polarization on the same cell junction (Bosveld et al., 2012; Brittle et al., 2012). However, it remains to be shown whether the polarization of Ds intracellular domain would be sufficient to polarize Dachs *in vivo*. The loss of Ft or Ds function in mutant clones leads to the formation of rounded clones minimizing their contact with neighboring tissues (Adler et al., 1998; Garoia et al., 2000; Mao et al., 2006). Loss of Ft activity induces apical cell constriction and results in the membrane accumulation of Dachs, and *ft* clone rounding depends on Dachs (Mao et al., 2006, 2011). Whether these changes in Dachs distribution are necessary for *ft* clone rounding remains to be determined.

Here, we investigated the role of loss of tumor suppressor and gain of proto-oncogene function in forming smooth clone boundaries in the *Drosophila* dorsal thorax (notum) epithelium where we could implement a time-lapse approach to follow the dynamics of clones. Initially focusing on the Ft/Ds pathway, we uncovered that *ft* clone rounding originates from two apparently opposed mechanical activities at the clone boundary and in the clone bulk. Extending the analysis to additional tumor suppressors and proto-oncogenes shows how distinct modulations of cell junction tension by tumor suppressors and proto-oncogenes could account for their common role in the regulation of cell-cell contacts.

RESULTS

A time-lapse approach to follow the rounding of *ft* clones

To understand the mechanisms of clone rounding we implemented a time-lapse approach to follow the dynamics of ft^{RNAi} clones within the notum epithelium during pupal development (Fig. 1A). Using a combination of the flip-out and temperature-sensitive Gal4/$Gal80^{ts}$ systems (Basler and Struhl, 1994; McGuire et al., 2001), the clones marked by the expression of membrane-CherryFP (UAS-PH:ChFP) were generated in second instar larvae that were then kept at 18°C to avoid the expression of the UAS-ft^{RNAi}. Following a temperature shift to 29°C at the end of larval development, we compared by time-lapse microscopy the proliferation and the circularity changes of a control group of cells and ft^{RNAi} clones (Fig. 1B-D; Movie 1). As a reporter of Ft activity we imaged Dachs:GFP (D:GFP), membrane levels of which increase upon loss of Ft function (Bosveld et al., 2012). At 10 hours after pupa formation (hAPF), the control and ft^{RNAi} clones had similar circularities and distributions of D:GFP. At 40 hAPF, whereas the control clones exhibited a reduced circularity and a D:GFP distribution similar to the surrounding cells, the ft^{RNAi} clones had a much higher circularity and an increased D:GFP level at cell junctions (Fig. 1B-D). This shows that our live-imaging approach is suitable for understanding how Ft/Ds signaling regulates tissue organization. To investigate whether clone rounding depends on cell division, we compared the respective timing of cell division and clone shape changes as well as the rates of proliferation in control and ft^{RNAi} clones (Fig. 1C). In both control and ft^{RNAi} clones, a wave of cell divisions occurred between 15 and 20 hAPF. During this wave neither the control nor the ft^{RNAi} clones rounded up. In fact, ft^{RNAi} clone rounding was observed after cell divisions had ceased and once D:GFP had started to accumulate (Fig. 1B). Furthermore, the proliferation rates were similar in control and ft^{RNAi} clones, showing that clone rounding can take place in the absence of over-proliferation (Fig. 1C). Together, these data show that rounding of ft^{RNAi} clones, and thus the reduction of their contacts with neighboring wt cells, is not concomitant with cell divisions and does not require a change in proliferation rate.

Dachs exhibits two distinct distributions in *ft* mutant clones

Having found that D:GFP accumulates in ft^{RNAi} clones during rounding and knowing that Dachs is necessary for *ft* clone rounding (Mao et al., 2006, 2011), we performed a detailed analysis of the distribution and the mechanisms of Dachs localization in *ft* clones. Ft signaling is known to prevent Dachs membrane accumulation (Mao et al., 2006, 2011; Bosveld et al., 2012; Brittle et al., 2012). Accordingly, D:GFP levels were increased in *ft* cells and sometimes segregated in distinct regions of the cell junctions (Fig. 2A; Figs S1, S2). We also noticed that D:GFP was strongly enriched all around the circumference of *ft* clones, i.e. at the interface between wt and *ft* cells, but reduced at the transversal junctions (Fig. 1B; Fig. 2A, yellow arrowheads). Quantitative analyses of the D:GFP distribution at clone boundary and transversal junctions revealed that D:GFP within mutant cells neighboring wt cells specifically accumulated at the clone boundary (hereafter referred to as 'Dachs polarization at clone boundary') (Fig. 2J). We therefore investigated the mechanisms leading to the polarization of D:GFP at the *ft* clone boundary. In agreement with the facts that the Ds intracellular domain forms a complex with Dachs *in vitro*, that Ds polarization promotes Dachs polarization and that Ds:GFP is polarized at the boundary of *ft* clones (Fig. 2B, yellow arrowheads; Strutt and Strutt, 2002; Ma et al., 2003; Matakatsu and Blair, 2004; Bosveld et al., 2012), D:GFP polarization was reduced at the boundary between wt and *ft ds* double mutant cells (Fig. 2C, white arrowheads; Fig. 2J). Whereas the overexpression of a full-length Ds transgene in *ft ds* clones (*ds ft* ds^{UP}) restores D:GFP polarization at the clone boundary (Fig. 2D, yellow arrowheads; Fig. 2J), overexpression of the Ds intracellular domain (Ds:intra) did not (Fig. 2E, white arrowheads; Fig. 2J), suggesting that the extracellular heterophilic Ds-Ft interaction is required to polarize Dachs. Accordingly, D:GFP polarization was reduced at the clone interface of *ds ft* ds^{UP} clones, which abutted a *ft* hypomorphic mutant tissue (compare Fig. 2D and 2F; Fig. 2J). Because loss of Ft activity inhibits Dachs membrane levels, D:GFP is also elevated in *ft* cells surrounding *ds ft* ds^{UP} clones. Together, our results support the hypothesis that Dachs is

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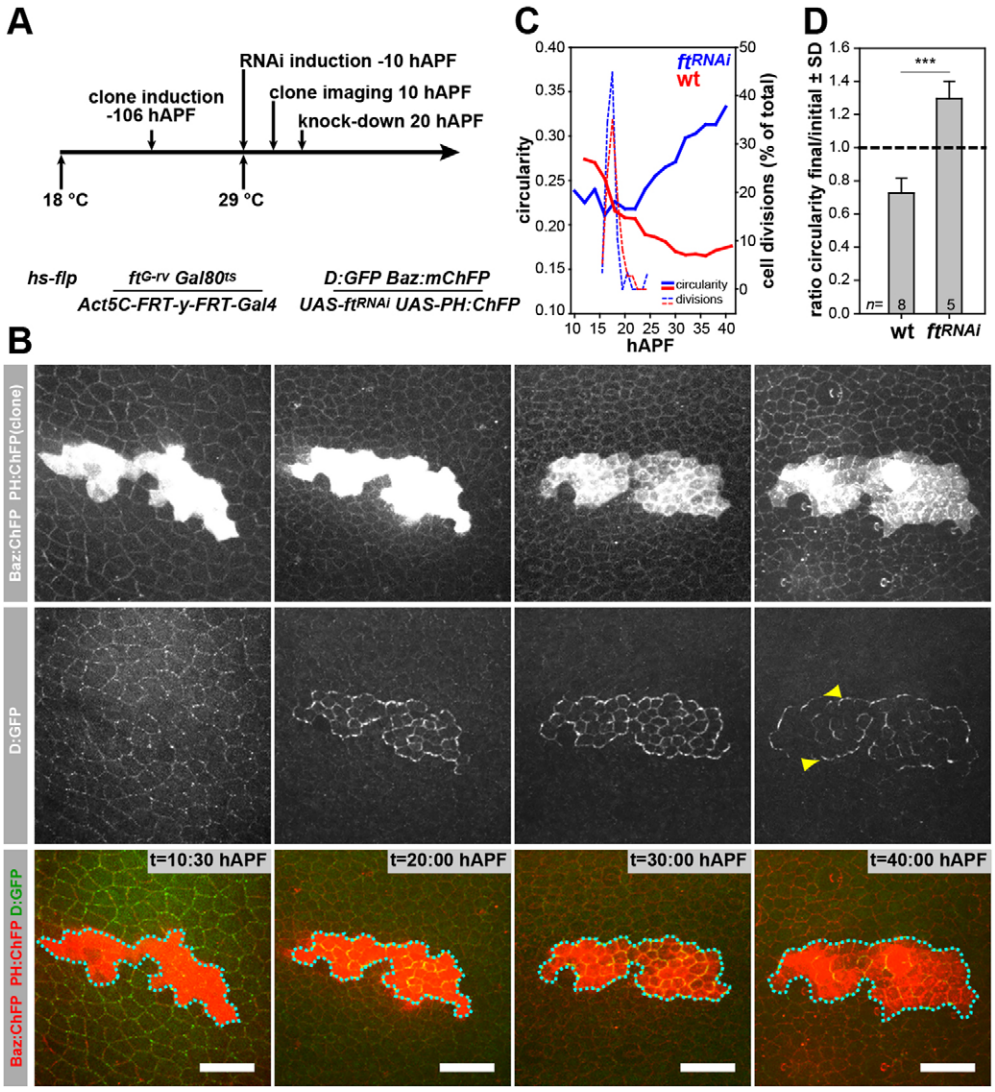

Fig. 1. Cell division and over-proliferation does not account for the increased circularity of *ft* clones. (A) Schematic illustrating the dynamics of Ft loss-of-function clones in pupa of the indicated genotype. Embryos and larvae were raised at 18°C for 7 days. Upon a 7-min heat-shock at 37°C larvae were returned to 18°C. After 4-5 additional days at 18°C, late third instar larvae were transferred to 29°C to induce expression of the *ft* dsRNA. After 22±4 h at 29°C 10 hAPF pupae were mounted and imaged at 29°C. Strong downregulation of Ft function, measured by increase in D:GFP relative to surrounding tissue, is observed at ∼20 hAPF (see B). (B) Images of Movie 1 showing a ft^{RNAi} clone labeled by PH:ChFP in a tissue expressing Baz:mChFP (white in top panels; red in bottom panels) and D:GFP (white in middle panels; green in bottom panels). Cyan dashed lines indicate clone boundaries. At 10:30 (h:min) hAPF, D:GFP localization is similar inside and outside of the ft^{RNAi} clone. At ∼20 hAPF, D:GFP is enriched in the ft^{RNAi} clone. Over time, D:GFP gradually accumulates and becomes polarized at the clone boundary. This clone becomes rounder over time (see C). Yellow arrowheads indicate cells where D:GFP is polarized. Scale bars: 20 µm. (C) Circularity (solid lines) and number of divisions (dashed lines) versus time for a wt clone (red) and the ft^{RNAi} clone (blue) shown in B. (D) Mean ratio of final/initial clone circularity of wt and ft^{RNAi} clones. ***P<0.0005 (t-test); n, clone numbers; error bars represent s.d.

not only enriched in *ft* mutant clones, but is also polarized at the clone boundary due to Ds polarization.

Two independent and complementary results strengthen the proposal that the polarization of the Ds intracellular domain is sufficient to polarize Dachs at the *ft* clone boundary. First, *in vitro* analyses of D:GFP polarization using an S2-induced polarity assay (Johnston et al., 2009; Ségalen et al., 2010), in which the extracellular and transmembrane domains of the homophilic adhesion molecule Echinoid are fused to the intracellular domain of Ds (Ed:mCh:Ds:intra), showed that the Ed:mCh:Ds:intra polarity domain was sufficient for D:GFP recruitment and polarization, which colocalized with Ed:mCh:Ds:intra (Fig. 2K). Second, within the tissue, we found that the circumference of clones that overexpressed a chimera of the Ds intracellular and Ft extracellular domains (Casal et al., 2006) in *ds ft* clones (*ds ft ds:intra:ft:extra*^{UP}) can harbor a D:GFP polarization at the clone interface (Fig. 2G, yellow arrowheads; Fig. 2J). Such polarization was lost in *ds:intra:ft:extra*^{UP} cells surrounded by *ds* cells (*ds ft ds:intra:ft:extra*^{UP} in *ds*; compare Fig. 2G and 2H; Fig. 2J), indicating that the polarization of the Ds intracellular domain appears to be sufficient to polarize Dachs independently of the orientation of the Ft-Ds extracellular heterophilic interaction. Altogether these results indicate that loss of Ft activity induces two distinct Dachs distributions within *ft* clones: an increase of Dachs levels within *ft* cells and a Dachs accumulation at clone boundary junctions in response to Ds intracellular domain polarization.

Two complementary activities of Dachs contribute to *ft* clone rounding

The identification of two distinct changes in Dachs distribution in *ft* clones prompted us to investigate their respective contribution to clone rounding. We previously found that D:GFP polarization at cell junctions correlates with a higher junction tension (Bosveld et al., 2012). To investigate further the role of Dachs polarization in junction tension regulation, we first confirmed that Dachs polarization promotes an increase in junction tension, i.e. the force exerted by the junction parallel to it, which is considered positive when it reduces junction length and which can be estimated by the initial recoil velocity of the junction vertices upon its severing by laser ablation (Hutson et al., 2003). As Ds planar polarization is independent of Dachs function (Fig. 3A-C; Bosveld et al., 2012; Brittle et al., 2012), we compared the relaxation velocity of junctions showing high or low Ds:GFP signal in a *dachs* tissue, the junctions being labeled by Baz:mChFP. The loss of Dachs function abolishes the difference in relaxation velocity between junctions bearing high and low Ds:GFP (Fig. 3D). Because Ds and Dachs are

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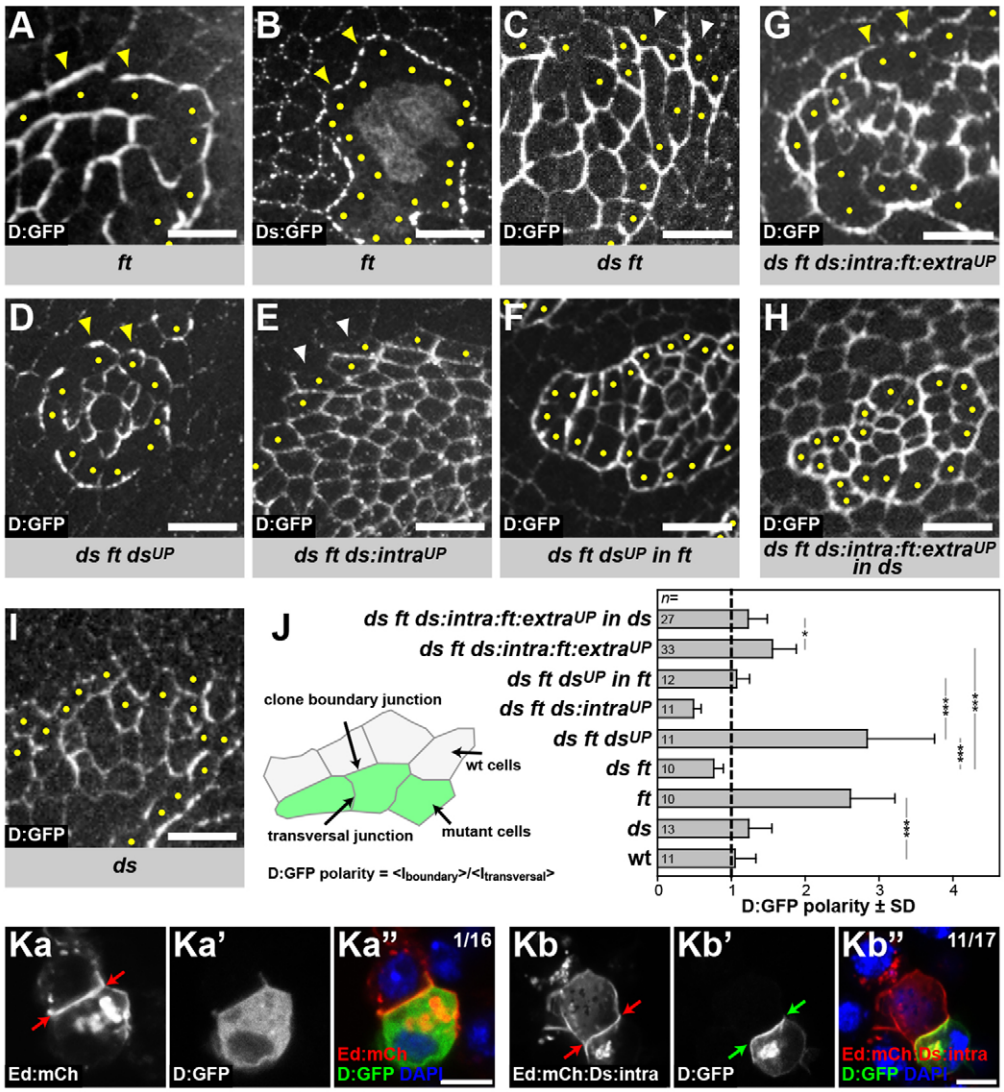

Fig. 2. Dachsous polarizes Dachs at *ft* clone boundaries. (A-I) D:GFP (A,C-I) and Ds:GFP (B) localization in clones and tissues of indicated genotypes. Yellow arrowheads indicate junctions where D:GFP or Ds:GFP are polarized whereas white arrowheads indicate the ones devoid of polarization. Yellow dots indicate mutant cells abutting wt cells. In agreement with previous findings (Ma et al., 2003), Ds staining appears cytoplasmic and diffuse inside the *ft* clone and remains at the membrane at the *ft* clone boundary. The Ft-Ds interaction might be needed to maintain Ds at the membrane (B). (J) Explanation of D:GFP polarity quantification. D:GFP is considered polarized when the ratio of the average junction intensity at clone boundaries ($<I_{boundary}>$) over the average junction intensity at transversal junctions ($<I_{transversal}>$) is >1. Graph shows D:GFP polarization at clone boundaries of indicated genotypes. *P<0.05, ***P<0.0005 (one-way ANOVA Tukey's test); *n*, clone numbers; error bars represent s.d. (Ka-Kb″) D:GFP polarization using an S2 induced polarity assay, in which the extracellular and transmembrane domains of the homophilic adhesion molecule Echinoid are fused to the intracellular domain of Ds (Ed:mCh:Ds:intra). Images of fixed S2 cell aggregates showing the polarized interface between two cells created by homophilic interaction of either Ed:mCh (Ka) or Ed:mCh:Ds:intra (Kb) (red arrows). In each doublet, one cell also expresses D:GFP (Ka′,Kb′). D:GFP does not localize to the polarized interface when co-expressed in cells expressing Ed:mCh (Ka′, Ka″), but is efficiently recruited to the interface when co-expressed with Ed:mCh:Ds:intra (Kb′,Kb″) (green arrows). Numbers in the top corner of Ka″ and Kb″ indicate the proportion of cells with polarized D:GFP (1 out of 16, and 11 out of 17). Scale bars: 10 µm (A-I); 5 µm (Ka″,Kb″).

planar polarized at the same junctions, this indicates that Dachs activity is necessary to increase the tension of junctions harboring Ds and Dachs polarization.

Having confirmed that Dachs polarization is necessary to increase cell junction tension in wt tissue, we tested whether the Dachs polarization at the boundary of *ft* clones and the increase in cell junction tension (Fig. 4A,B; Bosveld et al., 2012) are sufficient to fully explain the higher circularity of *ft* clones relative to wt clones. The increased tension at *ft* clone boundaries was independent of the clone size and the orientation of the ablated junctions (Fig. S3). The loss of Ds activity in *ft* mutant clones is associated with a decreased D:GFP polarization at clone boundaries (Fig. 2C,J) and an average junction tension similar to that of wt (Fig. 4C,C′). Although the circularity of *ds ft* clones was lower than the circularity of *ft* clones, the circularity of *ds ft* clones remained higher than that of wt clones (Fig. 4A). As Dachs activity is essential to increase the *ft* clone boundary tension and the circularity of *ft* clones (Fig. 4A,B; Mao et al., 2006), this indicates that Dachs polarization at the clone boundary increases the circularity of *ft* clones and that an additional Dachs-dependent mechanism inside the clone contributes to *ft* clone rounding (Fig. 1; Fig. 4A).

To identify this additional mechanism, we probed the tension of junctions inside *ft* clones. Unexpectedly, we observed that inside *ft* clones the average cell junction tension was reduced (Fig. 4B). A

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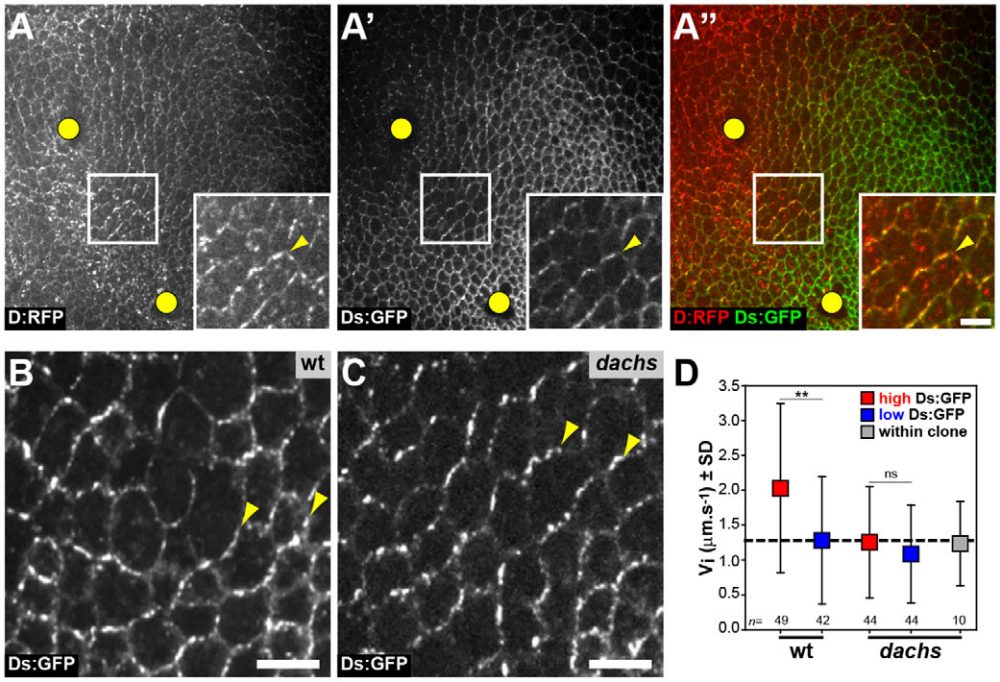

Fig. 3. Dachs regulates cell junction tension. (A-A″) Images of a right hemi-scutellum (posterior notum) tissue expressing D:RFP (white in A; red in A″) and Ds:GFP (white in A′; green in A″) at 18 hAPF. Insets show magnifications of the boxed regions. Yellow arrowheads indicate junctions where D:RFP and Ds:GFP are polarized. Yellow circles mark macrochaetae. In agreement with previous findings (Bosveld et al., 2012), D:RFP and Ds:GFP are planar polarized and colocalize within a restricted domain. This domain corresponds to the area where the *ds* and *fj* gene expression gradients overlap (Bosveld et al., 2012). Note that D:RFP tends to aggregate in small punctate structures. (B,C) Images of posterior notum tissue expressing Ds:GFP in wt (B) and *dachs* (C) tissue. Yellow arrowheads indicate junctions where Ds:GFP is polarized. (D) Tension changes determined by mean initial recoil velocity of vertices of ablated cell junctions with high (red) or low (blue) Ds:GFP levels within the Ds:GFP polarity domain in wt or *dachs* tissue, as well as within *dachs* clones (gray). ***P*<0.005; ns, not significant (*t*-test); *n*, junction numbers; error bars represent s.d. Scale bars: 5 µm.

lower tension inside the clone was also measured in *ds ft* and in *ds* clones, showing that the tension decrease is independent of Ds function (Fig. 4C,D). Cell junction tension inside *ft dachs*, *ds dachs* and *ds ft dachs* clones as well as their circularities were similar to the wt, indicating that Dachs activity is necessary inside *ft* clones to reduce junction tension (Fig. 4B-D). The changes in junction tension were not associated with changes in the levels of the *Drosophila* Myosin II light chain (Spaghetti Squash, Sqh) at the boundary of or inside *ft* or *ds* clones (Fig. 4E,F; Fig. S4).

A common feature of *ft*, *ds* and double *ds ft* clones is to exhibit a higher level of Dachs (Mao et al., 2006; Brittle et al., 2012; Fig. 2A,I; Fig. S1A,H), which is reported to inhibit Wts (Cho et al., 2006) via Zyxin-dependent or -independent mechanisms (Rauskolb et al., 2011; Gaspar et al., 2015). We uncovered that loss of Wts activity (wts^{RNAi}) leads to clone rounding and to a decrease of junction tension similar to that measured inside *ft*, *ds* or *ds ft* clones (Fig. 4G,H). Furthermore, overexpression of Wts in *ft* clones (*ft* wts^{UP}) partially rescued the rounding of *ft* clones by reducing the polarization of Dachs and the tension at clone boundary junctions (Fig. 4G-J). Finally, the lower tension associated with Wts loss of function might be mediated by the activation of Yki as clones overexpressing Yki (yki^{UP}) are characterized by a junction tension similar to that of wts^{RNAi} (Fig. 4G). yki^{UP} clones display a rounder shape than wts^{RNAi} clones (Fig. 4H), suggesting that overexpression of Yki promotes clone rounding by both tension-dependent and tension-independent mechanisms. Together, these experimental observations indicate that Dachs has two apparently opposed mechanical activities: the polarized Dachs distribution at the boundary of the clone increases junction tension and the Dachs accumulation within the clone bulk decreases junction tension.

Two opposed mechanical activities cooperate to promote clone rounding

Next, we aimed to understand better the impact of differential junction tension, and more specifically to determine how both opposed mechanical activities might cooperate to determine the rounding and thus the segregation of developing clones. Based on a theoretical analysis (Graner, 1993; supplementary materials and methods), we analyzed the competition between the tension of cell junctions at the clone boundary γ_b on the one hand, and the tensions of cell junctions within the clone γ_c, or in the surrounding wt cells γ on the other hand (Fig. 5A). Modeling and experiments are independent of the biological origin of these tensions. This analysis shows that: (1) there is an energy cost associated with the length of the clone boundary when junction tensions (γ,γ_b,γ_c) are different; and (2) the tendency of the clone to round up (decrease contact with wt neighbors), or in contrast to scatter (increase contact with wt neighbors), is determined by the sign and amplitude of the 'dimensionless clone tension' parameter:

$$\sigma = 1/\gamma\{\gamma_b - [(\gamma + \gamma_c)/2]\}. \quad (1)$$

It represents the energy cost per unit length of increasing the clone boundary by changing 'homotypic' junctions (wt-wt or mutant-mutant) into 'heterotypic' boundary junctions (wt-mutant), and should not be confused with the cell junction tensions themselves that are probed with laser ablations. An advantage of this description is that it takes into account junction tensions only with respect to their relative values, which are directly extracted from laser ablation experiments. The expression of σ is general and includes the case where the tensions on both sides of a domain boundary are the same,

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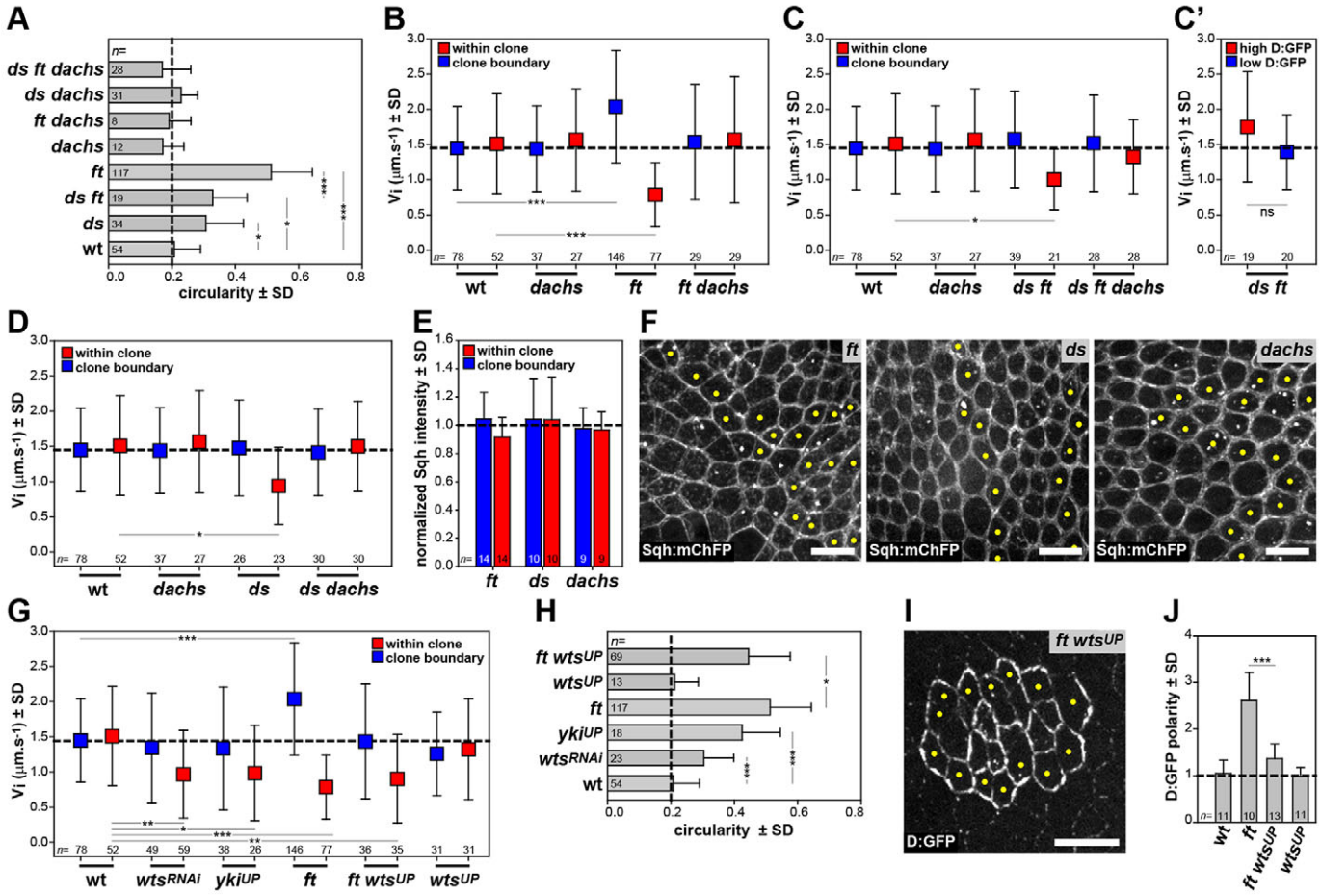

Fig. 4. Dachs has two distinct mechanical activities. (A) Mean clone circularity in the indicated genotypes. (B-D) Mean initial recoil velocity of vertices of ablated cell junctions at clone boundaries (blue) or junctions inside clones (red) of the indicated genotypes (B,C,D) and of junctions with high D:GFP (red) or low D:GFP (blue) at *ds ft* clone boundaries (C′). In *ds ft* clones, the tension of boundary junctions harboring high or low D:GFP are not different (P=0.08, *t*-test). (E) Normalized Sqh:ChFP intensity at clone boundary (blue) and bulk junctions (red) in *ft*, *ds* and *dachs*. (F) Sqh:ChFP localization in *ft* (left), *ds* (middle) and *dachs* (right) mutant clones. Yellow dots mark mutant cells abutting wt cells. (G) Mean initial recoil velocity of vertices of ablated cell junctions at clone boundaries (blue) or junctions inside clones (red) of the indicated genotypes. (H) Mean clone circularity in the indicated genotypes. (I) Image showing D:GFP localization in a *ft* wts^{UP} clone. Yellow dots mark mutant cells abutting wt cells. (J) D:GFP polarization at wt, *ft* and *ft* wts^{UP} clone boundaries. In all graphs, *P<0.05, **P<0.005, ***P<0.0005 (one-way ANOVA Tukey's test for A,H,J; one-way ANOVA Dunnett's test for B,C,D,G); ns, not significant (*t*-test for C′); *n*, clone numbers (A,E,H,J) or junction numbers (B-D,G); error bars represent s.d. Scale bars: 10 µm.

namely $\gamma_c=\gamma$ (Landsberg et al., 2009). It emphasizes that the junction tensions around and within the clone act antagonistically to contribute to the clone boundary energy cost. We therefore expect that when σ is positive, the clone boundary becomes more regular and its circularity increases, thus reducing contact with neighboring wt cells. By contrast, when σ is negative, the heterotypic (wt-mutant) junctions are favored and clones would gradually become more scattered. In between, when σ is null, which corresponds to a wt clone in a wt tissue, we expect it to become slightly more ragged over time (partly as a result of cell division randomly oriented with respect to clone boundary). Importantly, this agrees with our experimental observations: (1) wt clone circularity decreases over time (Fig. 1C); and (2) ft^{RNAi} clone circularity increases over time (Fig. 1C). This is illustrated in the graphs (Fig. 5B,D; Fig. S5B) showing the sign of σ versus the junction tensions at the clone boundary (γ_b) and inside the clone (γ_c) measured in wt, *ft*, *ds*, *ds ft* and wts^{RNAi} clones (Fig. 4B-D,G).

Using numerical simulations, we challenged more quantitatively this modeling by simulating the growth and proliferation of mutant clones using the cellular Potts model directly based on the ratios of experimental tension (Fig. 5C,D; Fig. S5; Movie 3). They showed that: (1) the experimental tension values in wt, *ft*, *ds* and *ds ft* both at clone boundary and inside the clone agree with the rounding of *ft* clones and the lower circularity of *ds* and double *ds ft* clones (Fig. 5D); (2) the combination of an increase of junction tension at the clone boundary and a decrease of junction tension inside the clone leads to a higher circularity than an increase of junction tension solely at the clone boundary (compare ft, simulated using tensions γ_b and γ_c with ft_b, simulated using γ_b and $\gamma_c=\gamma$; Fig. S5B); and (3) the dimensionless clone tension is relevant, and the observed clone circularity increases with σ similarly in experiments and in simulations (Fig. 5D; Fig. S5B). Our experimental observations and modeling of the *ft* clones uncovers how two distinct activities of the myosin Dachs associated with two distinct changes in its localization could induce clone rounding (reducing their contact with neighboring wt cells) by both increasing junction tension at the clone boundary and reducing it inside the clone.

Overexpression of proto-oncogenes modulates junction tension

Having found that the modulation of junction mechanical properties by the Ft/Ds and Hippo/Yki pathways promote clone rounding, we investigated whether the overexpression of proto-oncogenes known

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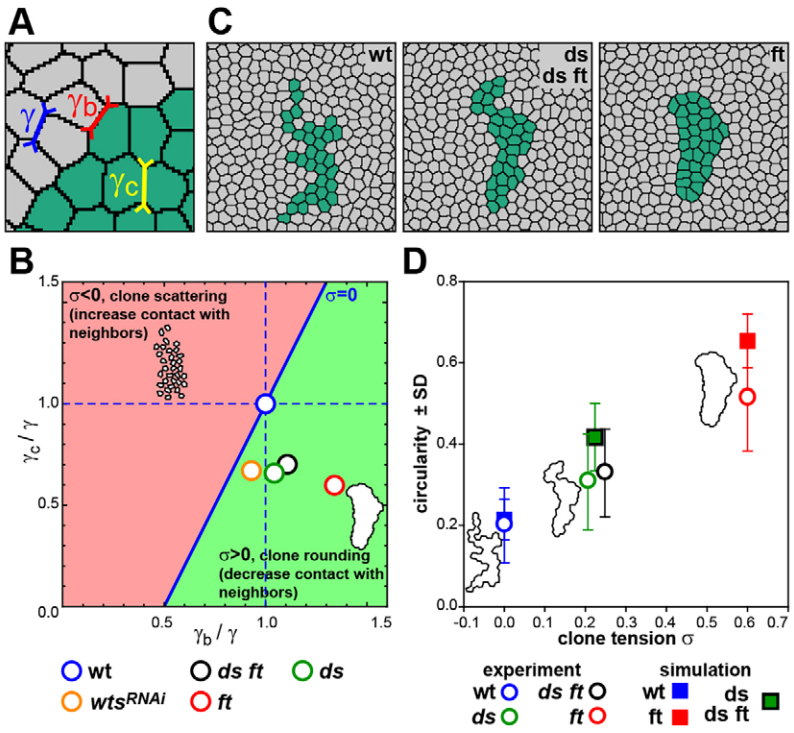

Fig. 5. Balance of cell junction tension accounts for somatic clone rounding. (A) Junction tension parameters used for simulations were: wt (γ, blue), clone boundary (γ_b, red), clone bulk (γ_c, yellow). γ_b/γ and γ_c/γ for each genotype were obtained from average experimental recoil velocities (Fig. 4B-D,G). (B) Parameter space of line tension ratios (γ_b/γ, γ_c/γ) showing regions where clones are expected to scatter (red, σ<0), or to round up (green, σ>0). Blue line (σ=0) separates the two regions and contains the wt clone in a wt tissue (γ_b/γ,γ_c/γ)=(1,1). Note that the domain to which a clone belongs, and its distance to the blue line, which represents its tendency to round up or scatter, solely depend on the sign and value of the dimensionless clone tension σ, respectively. wt: σ=0, *wts*^{RNAi}: σ=0.10, *ds*: σ=0.21, *ds ft*: σ=0.23, *ft*: σ=0.60. (C) Final images of simulated clones (green) using average experimental tension values. Owing to similarities of γ_b and γ_c in *ds* and *ds ft*, their means were used for *ds* and *ds ft* simulations. See Movie 2. (D) Mean clone circularity in experimental (circles) and simulated (squares) clones versus the dimensionless clone tension σ. Clone outlines (C) illustrate clone circularity. Twenty simulations were quantified per condition; error bars represent s.d.

to be associated with clone rounding also modulates junction tension. As previously reported (Prober and Edgar, 2000, 2002), we observed that the overexpression of Myc (*myc*^{UP}) as well as the overexpression of a gain-of-function allele of Ras (*rasV12*^{UP}) promote clone rounding (Fig. 6A). Probing the junction tension at the boundary and inside *myc*^{UP} and *rasV12*^{UP} clones unveiled distinct regulations of bulk or clone boundary junction tension as observed in the case of Ft/Ds or Hippo/Yki pathways (Fig. 6B). Whereas junction tension was reduced inside *myc*^{UP} clones and unchanged at the boundary, the junction tension was unchanged inside *rasV12*^{UP} clones but greatly increased at the boundary. The measured changes in junction tension are compatible with the rounding of somatic clones shown by our computer simulations (Fig. S5B). As the overexpression of Myc and RasV12 are both known to be associated with over-proliferation (Prober and Edgar, 2000, 2002), their distinct impacts on junction tension strongly suggest that over-proliferation cannot be the only cause of their clone rounding. Accordingly, and as observed for the development of Gal4/Gal80^{ts} *ft*^{RNAi} clones, the proliferation rate in Gal4/Gal80^{ts} *rasV12*^{UP} clones was similar to that of control clones, and *rasV12*^{UP} clone rounding was observed after the main cell division wave (Fig. 6C-E). We therefore investigated whether the observed changes in junction tensions and in clone circularities were associated with altered myosin distributions.

In *myc*^{UP} clones, D:GFP was not polarized at the interface of the clone. Furthermore, a heterogeneous D:GFP enrichment was observed at only a few *rasV12*^{UP} clone boundaries, and this enrichment was weak (Fig. 6I,J). Such a weak increase is unlikely to be responsible for the *rasV12*^{UP} clone circularity, which is similar to that of *ft* clones. Moreover, in all experimental conditions, the D:GFP levels were normal inside the clones. We therefore turned our attention to the distribution of MyoII (Sqh:GFP). *rasV12*^{UP} clones were associated with an increase in MyoII localization at the clone boundaries (Fig. 6F,H). Such an increased level of MyoII at the boundary of *rasV12*^{UP} clone is in full agreement with the observed higher tension also reported for the MyoII distribution along the anterior-posterior compartment boundaries or during cell intercalation (Rauzi et al., 2008; Fernandez-Gonzalez et al., 2009; Monier et al., 2010; Umetsu et al., 2014). In contrast to *rasV12*^{UP}, MyoII was globally reduced within *myc*^{UP} clones (Fig. 6F,G). To determine whether the reduction of MyoII levels can account for the rounding of *myc*^{UP} clones, we tested whether mimicking a reduction of MyoII levels using *sqh*^{RNAi} was sufficient to decrease junction tension and to induce a rounded clone shape. Indeed, reducing MyoII levels led to a reduced tension inside *sqh*^{RNAi} clones and promoted clone rounding (Fig. 6A,B).

DISCUSSION

The segregation of tissues or of tissue compartments plays fundamental roles in the regulation of growth, patterning and morphogenesis (for a review, see Fagotto, 2014). Numerous tumor suppressors and proto-oncogenes share the common feature of promoting cell segregation apparent by the rounding of somatic clones upon their loss or gain of functions, respectively (Adler et al., 1998; Johnston et al., 1999; Prober and Edgar, 2000, 2002; Garoia et al., 2000; Baena-Lopez et al., 2005; Mao et al., 2006, 2011; Worley et al., 2013). Here, we show that loss of Ft/Ds and Hippo tumor-suppressor pathways as well as gain of function of the proto-oncogenes Myc, Ras and Yki lead to changes in cell junction tension. Although the changes are distinct and depend on distinct molecular mechanisms, taking into account both clone boundary and bulk tensions is sufficient to account for their segregation from surrounding wt tissue. Although previous works demonstrated that cell cortical contractility or cell adhesion at the interface between two compartments, tissues or clones can promote their separation or contribute to tissue invagination (Graner, 1993; Le Borgne et al., 2002; Brodland, 2002; Wei et al., 2005; Laplante and Nilson, 2006; Landsberg et al., 2009; Monier et al., 2010; Chang et al., 2011; Aliee et al., 2012; Röper, 2012; Fagotto et al., 2013; Calzolari et al., 2014; Umetsu et al., 2014), our genetic and modeling findings show that

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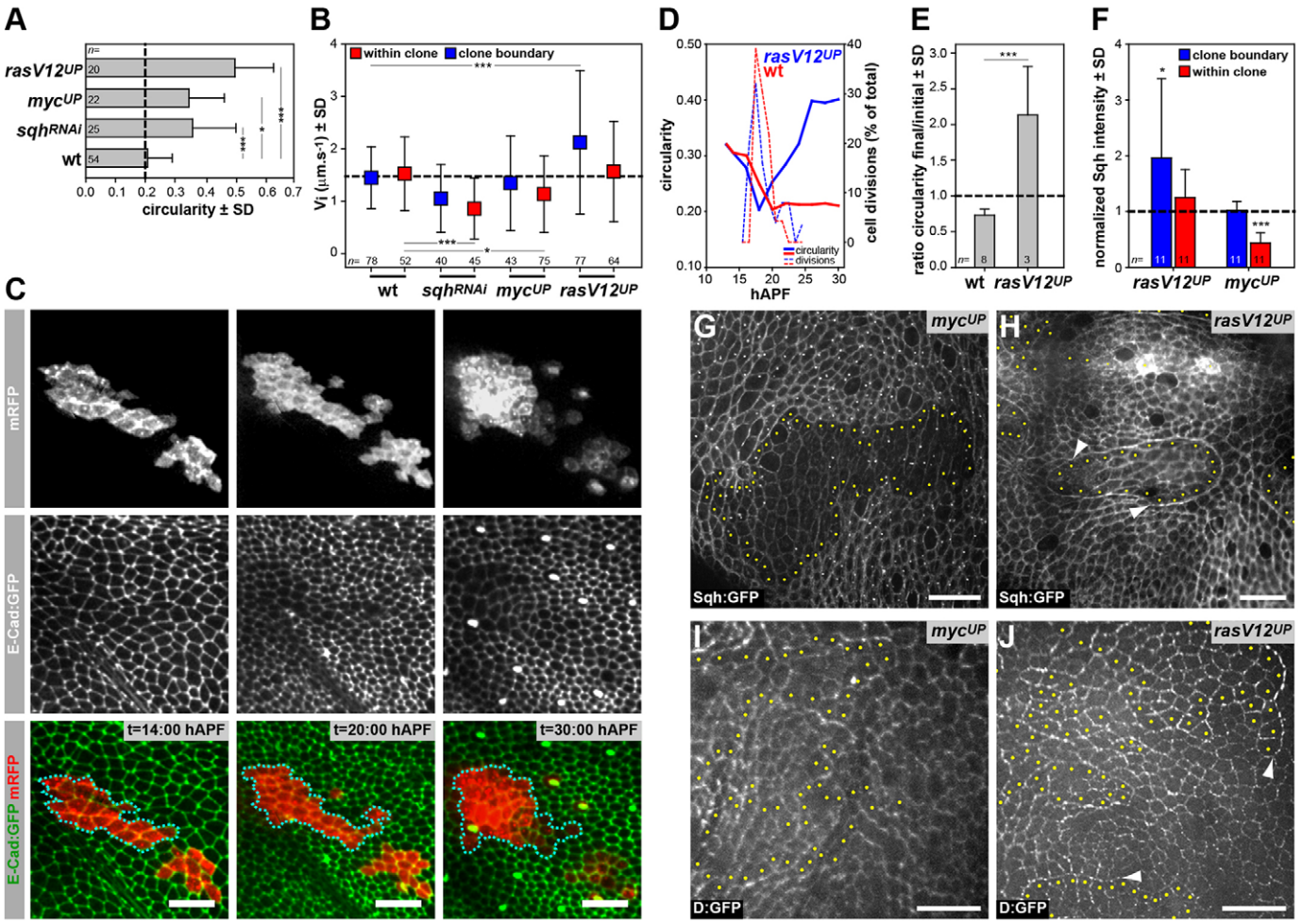

Fig. 6. Proto-oncogene overexpression affects cell junction tension and clone rounding. (A) Mean clone circularity in the indicated genotypes. (B) Mean initial velocity of vertex relaxation after ablation of cell junctions at clone boundaries (blue) or junctions inside clones (red) of the indicated genotypes. (C) Images of Movie 3 showing a *rasV12*^{UP} clone (imaged as in Fig. 1) labeled by mRFP (white in top panels; red in bottom panels) in a tissue expressing E-Cad:GFP (white in middle panels; green in bottom panels). Cyan dashed lines indicate clone boundaries. This clone becomes rounder over time (see D). (D) Circularity (solid lines) and number of divisions (dashed lines) versus time of a wt clone (red) and the *rasV12*^{UP} clone (blue) shown in C. (E) Mean ratio of final/initial clone circularity of wt and *rasV12*^{UP} clones. (F) Normalized Sqh:ChFP intensity at clone boundary (blue) and bulk junctions (red) in *rasV12*^{UP} and *myc*^{UP} clones. (G-J) Sqh:GFP (G,H) and D:GFP (I,J) localization in *myc*^{UP} (G,I) or *rasV12*^{UP} (H,J) clones. Yellow dots indicate mutant cells abutting wt cells. Sqh:GFP levels are reduced in *myc*^{UP} (G; quantified in F) whereas Sqh:GFP is enriched at clone boundaries of *rasV12*^{UP} (H, white arrowheads; quantified in F). D:GFP distribution and levels are unaffected in *myc*^{UP} (I), whereas D:GFP is enriched at some *rasV12*^{UP} clone boundaries (J, white arrowheads). In all graphs, **P*<0.05, ****P*<0.0005 (one-way ANOVA Tukey's test for A; one-way ANOVA Dunnett's test for B; *t*-test for E,F); *n*, clone numbers (A,E,F) or junction numbers (B); error bars represent s.d. Scale bars: 20 µm.

both boundary and bulk cell junction tensions need to be considered to fully account for segregation. This point is illustrated by the analysis of the mechanisms of clone rounding in the case of the Ft/Ds pathway where loss of Ft activity leads to change in cell junction tension both at the clone boundary and within the clone bulk.

We provide evidence that the rounding of *ft* clones can result from two apparently opposed mechanical inputs that require Dachs myosin activity. On one hand, the polarization of Ds at clone boundaries promotes Dachs polarity and increases junction tension. On the other hand, loss of Ft or Ds activity in the bulk of the clone leads to elevated Dachs levels and a decrease in junction tension. Our genetic and modeling findings show how these two distinct mechanical inputs both contribute to *ft* clone rounding. Importantly, increased levels of Dachs lead to an increased junction tension only at cell junctions where both Ds and Dachs are polarized, providing the first example of polarization and changes in the levels of a myosin leading to opposite changes in junction tension. The mechanism by which Dachs increases junction tension upon Ds-dependent polarization within tissues might be distinct from the one proposed for MyoII, because *in vitro* recombinant Dachs does not bind F-Actin in an ATP-dependent manner, but rather modulates F-Actin organization by promoting the binding of Zyxin to F-Actin (Cao et al., 2014). The mechanisms by which Dachs reduces tension inside *ft* and *ds* clones are independent of Ft and Ds activity and correlate with an increase of Dachs level. Dachs is reported to inhibit Wts by both Zyxin-dependent and -independent mechanisms (Rauskolb et al., 2011; Gaspar et al., 2015) and loss of Wts activity is associated with a similar decrease of cell junction tension. Wts is localized at cell-cell junction and its activity correlates with its binding to distinct partners and with distinct apical-basal distributions (Rauskolb et al., 2014; Sun et al., 2015). Whether these changes in Wts binding partner at cell-cell junctions can account for the regulation of tension by Dachs remains to be analyzed. Finally, the Ft/Ds pathway controls the shape of mammalian tissue (Saburi

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et al., 2008), therefore it will be relevant to examine whether Ft and Ds regulate tissue shape in vertebrate systems through modulation of cell junction tension.

Our findings on the mechanisms of clone rounding provide information on cell competition and on a possible negative feedback between proliferation and tension regulation. In the context of cell competition, it has been recently reported that a clonal decrease of Myc levels, or a clonal increase of Myc levels in conjunction with an inhibition of apoptosis, promotes clone fragmentation and cell mixing; such cell-cell mixing increases cell-cell contacts and depends on reduced levels of F-actin, independently of changes in MyoII levels (Levayer et al., 2015). Our experimental results and previous findings show that Myc overexpression leads to clone rounding and a reduction of cell-cell contacts with neighboring wt cells (Prober and Edgar, 2002). Although we did not study Myc-mediated cell competition and our experimental setup was different from that of Levayer et al. (2015), it would be relevant to analyze whether Myc-mediated cell competition also depends on additional mechanisms associated with reduced cell-cell contact formation owing to a decrease of MyoII level. Lastly, our findings on Yki suggest the existence of a possible negative feedback between Yki activation and cell junction tension. Both experimental and modeling approaches converge to support the idea that mechanical tension is an important regulator of growth and proliferation (Shraiman, 2005; Hufnagel et al., 2007; Aegerter-Wilmsen et al., 2007, 2012; Mammoto and Ingber, 2010; Dupont et al., 2011; Sansores-Garcia et al., 2011; Aragona et al., 2013; Schluck et al., 2013; Rauskolb et al., 2014; Benham-Pyle et al., 2015). In particular, an increase in mechanical tensile stress leads to the activation of the Hippo/Yki (YAP/TAZ) pathway (Dupont et al., 2011; Sansores-Garcia et al., 2011; Rauskolb et al., 2014; Codelia et al., 2014). We have provided evidence that ectopic activation of the Hippo/Yki pathway in the notum epithelial tissue decreases junction tension in the bulk of the clone. The decrease of junction tension upon activation of Yki might unveil the possible existence of negative feedback from Hippo and Yki signaling in response to tensile stress in *Drosophila* tissues. Although the exact molecular mechanisms remain to be better characterized, we propose that such negative feedback could be instrumental to prevent prolonged activation of the Hippo and Yki pathways in response to an increase of mechanical tissue tension associated with tissue development or with external stress. Finally, by demonstrating that other signaling pathways regulate clone bulk or boundary tensions, we foresee that junction tension regulation might support cross-talk between tumor suppressor/proto-oncogene pathways and the Hippo/Yki pathways to define the size and shape of tissues and organs.

MATERIALS AND METHODS

Fly stocks

Drosophila stocks used were: ds^{05142}, $ft^{G\text{-}rv}$, ft^{8}, ft^{1}, d^{GC13}, d^{210}, UAS-ft^{RNAi}, UAS-sqh^{RNAi}, UAS-wts^{RNAi}, UAS-*yki*, UAS-*myc*, UAS-Ras^{V12} (see Table S1 for full genotypes and references). Clones were generated using FLP/FRT, flip-out or mosaic analysis with a repressible cell marker (MARCM) techniques (Xu and Rubin, 1993; Basler and Struhl, 1994; Lee and Luo, 1999). Clones were induced in second instar larvae (20 min heat-shock at 37°C) and analyzed 3-4 days later in 18-22 hAPF pupa. Live-imaging was carried out on ft^{RNAi} (*hs-flp;* $ft^{[G\text{-}rv]}$, *tub-GAL80*$^{[ts]}$*/AyGAL4; D:GFP, Baz:mChFP/UAS-*$ft^{[RNAi,\ JF03245]}$, *UAS-PH:ChFP*), *rasV12* (*hs-flp; UAS-ras*$^{[V12]}$*/E-Cad:GFP, tub-GAL80*$^{[ts]}$*; tub-FRT-GAL80-FRT-GAL4, UAS-mRFP*); clone induction and temperature changes are listed in the legend of Fig. 1 with further details in supplementary materials and methods. Their behaviors were compared with control clones: groups of 25-50 cells, with a circularity similar to that of ft^{RNAi} or $rasV12^{UP}$ clones at the onset of pupariation (10 hAPF), were tracked in a region of the epithelial tissue devoid of ft^{RNAi} clones (n=4) or in E-Cad:GFP pupae filmed at 29°C (n=4). Clones were analyzed in the anterior notum where the Ds and Fj gradients are absent and where cells undergo only one division (Bosveld et al., 2012).

Imaging, laser ablations, quantification of junction tension, and immunohistochemistry

Pupae were mounted and imaged at 25°C or 29°C using an inverted confocal spinning disk microscope (Nikon) (David et al., 2005). Time-lapse images were acquired every 10 min (0.5 µm/slice, 20-30 slices/z-stack). Images of live or fixed pupae were captured in 18-22 hAPF pupae.

Laser ablations were performed in 18-22 hAPF pupae using a Ti:Sapphire laser (Mai Tai DeepSee, Spectra Physics) and images were acquired using a two-photon laser-scanning microscope (LSM710 NLO, Carl Zeiss) in single-photon mode with bidirectional scan lasting 156 ms in a region of 18 µm x 18 µm (100×100 pixels) as previously described (Bosveld et al., 2012). Ablations were performed in tissues expressing D:GFP and Baz:mChFP (wt, *ft*, *ds*, *ds ft*), Ds:GFP and Baz:mChFP (wt, *dachs*), Baz:mChFP (*ft dachs*, *dachs*) or E-Cad:GFP (*ft*, *dachs*, *ds dachs*, *ds ft dachs*, myc^{UP}, yki^{UP}, $rasV12^{UP}$, sqh^{RNAi}, wts^{RNAi}, wts^{UP}, *ft* wts^{UP}). To determine the initial relaxation velocity, the vertex-vertex distance of the pre-cut and post-cut (two frames after ablation) junction was measured manually using ImageJ. For each given ablation, the relative uncertainty on the velocity measurement was of order of 5%, much lower than the biological variability between different ablation experiments.

For immunohistochemistry, pupae were dissected, fixed and stained as described by Ségalen et al. (2010). Primary antibodies used were rabbit anti-GFP (1:2000; A-11122, Molecular Probes) and mouse anti-FasIII (1:50; DSHB 7G10). Secondary antibodies were Cy3-conjugated donkey-anti-mouse (Jackson ImmunoResearch) and Alexa-488-conjugated goat-anti-rabbit (Molecular Probes). Images were collected with a confocal microscope (LSM710 NLO, Carl Zeiss).

Quantification of clone circularity

In the literature, the terms ‘circularity’, ‘compactness’, ‘segregation’ or ‘separation’ are used to express a size reduction of the contact with neighboring cells and can be quantified by measuring the clone area to square perimeter ratio ($C=4\pi\times\text{area}/\text{perimeter}^2$). C=1 for a circle. Circularity quantifications were performed on fixed and live tissues using membrane markers (mRFP, PH:ChFP, FasIII, Baz:mChFP, E-Cad:GFP) to delineate clone outlines. Clones were identified using loss (ubi-nlsGFP, ubi-H2B:RFP) or gain (UAS-GFP, UAS-mRFP, UAS-PH:ChFP) of expression. Clone outlines were manually drawn and measured using ImageJ.

Quantification of D:GFP polarity and junctional intensity of Sqh:ChFP/Sqh:GFP

D:GFP polarity was quantified by measuring on average projected images the D:GFP intensity at clone boundary junctions and transversal junctions within clones. The intensity was quantified manually (~10-40 transversal, ~20-60 boundary junctions per clone) and corrected by subtraction of the cytoplasmic signal. For each clone, the ratio between the average intensity at boundary junctions ($<I_{boundary}>$) and average intensity at transversal junctions ($<I_{transversal}>$) was determined. D:GFP is polarized when the ratio is >1. Junctional Sqh:ChFP or Sqh:GFP levels were quantified by manually measuring on average projected images the intensity on junctions inside clones, at clone boundaries as well as in wt junctions surrounding the clone. In each clone, ~15-50 boundary, bulk and wt junctions were measured. The intensities were corrected by subtraction of the cytoplasmic signals. Boundary and bulk junctional intensities were normalized to the wt junctional intensity to determine the average boundary and bulk intensities per clone.

Molecular biology, S2 cell culture and polarity assay

The Ubi-Dachs:mRFP transgene was generated by cloning a full length *dachs* cDNA (D isoform) into pUWR (DGRC) by Gateway cloning. Transgenesis was performed by Bestgene Inc. For the S2 cell polarity assay, the Ds intracellular domain was fused to the extracellular domain of echinoid

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fused to mCherry (Ed:mCh:Ds:intra). The Ds intracellular fragment used in the S2 cell polarity assay was cloned into pMT:Ed:mCherry with a five-amino acid linker (GGGGS) between the mCherry and the Ds intracellular domain. Dachs was cloned into pUWG (DRGC). Induced cell polarity assays were carried out as described previously (Johnston et al., 2009; Ségalen et al., 2010). The polarization of the GFP-tagged Dachs construct relative to the induced Ed:mCh:Ds:intra polarity interface was quantified from single confocal scans as follows. The mean GFP intensities all around the cell cortex $I_{cell\text{-}cortex}$ and at the Ed:mCh:Ds:intra interface $I_{polarity\text{-}domain}$ were quantified blindly using ImageJ. The D:GFP was scored as polarized when the $I_{polarity\text{-}domain}/I_{cell\text{-}cortex}$ ratio was >1.1.

Theoretical analysis of clone shapes and numerical simulations

See supplementary materials and methods for theoretical analysis and numerical simulations.

Statistics

All error bars represent the standard deviation (s.d.). Statistical significance between experimental conditions was assessed using Student's *t*-tests: distribution normalities were checked using Kolmogorov–Smirnov test. In cases where the variances were different (*F*-test), significance was assessed using the unequal variance *t*-test. The one-way ANOVA Tukey's test was used to assess significance between genotypes within the same dataset (circularity, D:GFP polarity). Significance between either clone boundary or clone bulk tensions was assessed using one-way ANOVA Dunnett's test. By reporting significances based on one-way ANOVA, statistical differences between two different experimental conditions might have been missed.

Code availability

The code used for simulations based on the cellular Potts model is provided as a zip file in supplementary information along with the procedure to install and run it on MacOS.

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Competing interests

The authors declare no competing or financial interests.

Author contributions

F.B. and Y.B. designed the project. F.B., I.B. and Z.W. performed experiments. Z.W. produced reagents. B.G. and M.R. wrote scripts to analyze data. F.B., B.G. and Y.B. analyzed the data. B.G. and F.G. developed the theoretical analysis. B.G. performed simulations. F.B., B.G., F.G. and Y.B. wrote the manuscript.

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Supplementary information

Supplementary information available online at
http://dev.biologists.org/lookup/suppl/doi:10.1242/dev.127993/-/DC1

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