Changes in blood cell deformability in Chorea-Acanthocytosis and effects of treatment with dasatinib or lithium

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Abstract

Misshaped red blood cells (RBCs), characterized by thorn-like protrusions known as acanthocytes, are a key diagnostic feature in Chorea-Acanthocytosis (ChAc), a rare neurodegenerative disorder. The altered RBC morphology likely influences their biomechanical properties which are crucial for the cells to pass the microvasculature. Here, we investigated blood cell deformability of 5 ChAc patients compared to healthy controls during up to one-year individual off-label treatment with the tyrosine kinases inhibitor dasatinib or several weeks with lithium. Measurements with two microfluidic techniques allowed us to assess RBC deformability under different shear stresses. Furthermore, we characterized leukocyte stiffness at high shear stresses. The results show that blood cell deformability – including both RBCs and leukocytes - in general is altered in ChAc patients compared to healthy donors. Therefore, this study shows for the first time an impairment of leukocyte properties in ChAc. During treatment with dasatinib or lithium, we observe alterations in RBC deformability and a stiffness increase for leukocytes. The hematological phenotype of ChAc patients hints at a reorganization of the cytoskeleton in blood cells which partly explains the altered mechanical properties observed here. These findings highlight the need for a systematic assessment of the contribution of impaired blood cell mechanics to the clinical manifestation of ChAc.

1 Introduction

Chorea-acanthocytosis/VPS13A disease (ChAc) is a rare monogenetic neurodegenerative disease of the young adulthood affecting multiple systems other than the central nervous system, e.g., the red blood cells (RBCs) (1–3). ChAc is characterized by various movement disorders (due to a degeneration mainly of striatal neurons), epilepsy, cognitive decline and misshaped spiky RBCs, the latter being referred to as acanthocytes (1,2,4,5). The autosomal-recessive condition is caused by loss of function mutations in the *vacuolar protein sorting 13 homolog A* (*VPS13A*) gene (6–10). Therefore, the term "VPS13A disease" has been recommended to replace the historical, more descriptive terminology (11). A disease-modifying therapy has not been established so far.

It is still unclear, how exactly the loss of function of VPS13A leads to the manifestation of the cellular and clinical phenotype. VPS13A localizes at different membrane contact sites and is most probably involved in non-vesicular lipid transport as it is assumed also for the other members of the VPS13 protein family (for review, see Leonzino, Reinisch and De Camilli, 2021) (12–15). Two downstream mechanisms are considered to be important drivers of ChAc pathophysiology: decreased phosphoinositide-3-kinase (PI3K) signaling and increased activity of Src family tyrosine kinase Lyn (for review, see Peikert et al. 2018 (2)).

Active Lyn kinase accumulates in ChAc RBCs and hyperphosphorylates membrane proteins such as band 3 protein. Since band 3 is a structural protein, linking the cytoskeleton to the plasma membrane, it is likely to be causally involved in the genesis of the spiky morphology. Accumulation of active Lyn kinase was also found to be related to impaired autophagic flux (16,17). These phenotypes could be reversed by *in vitro* treatment with tyrosine kinase inhibitors (TKI) such as the Src kinase family inhibitor dasatinib (16). In a Vps13a knockout mouse model, the more specific Lyn kinase inhibitor nilotinib improved both the hematological and neurological phenotypes by improving autophagy and preventing neuroinflammation (18). In their recent work, Peikert et al., 2021 (19) report on single individual treatment approaches targeting Lyn kinase with dasatinib in ChAc patients. They showed that initially reduced F-actin signal, increased osmotic fragility and impaired autophagy were partially restored in ChAc RBCs.

Furthermore, disturbed signaling via Phosphoinositide-3-kinase (PI3K) has been also identified as relevant in the pathophysiology of ChAc patients. Reduced signaling via the PI3K-Rac1-PAK pathway was reported to lead to disordered actin polymerization (20). Additionally, in other cells, altered PI3K signaling caused a decreased ORAI1 expression and store-operated Ca^{2+} entry (SOCE), subsequently disturbed Ca^{2+} homeostasis and apoptosis which could be partly reversed by *in vitro* lithium treatment (21–23).

The rather late onset of the disease at the age of early adulthood and the slow progression rate (1,3,24) lead to the assumption of a dependency between the altered RBC properties and neuronal degeneration: Changes in the mechanical properties of the RBCs and hence reduced passage in micro-vessels and capillaries may impair oxygen supply in certain areas of the brain that could over time accumulate to tissue alterations leading to the symptoms described (25).

Altered RBC morphology is often linked to a change in cell mechanics which may lead to impaired blood flow (26,27). Until now, the effect of acanthocytes in ChAc patients on the pathophysiology of the disease remains elusive. Here, we describe, for the first time, altered deformability of blood cells from ChAc patients including white blood cells. In a second step, we observed these parameters during individual off-label treatments with dasatinib or lithium, each targeting one of the signaling pathways believed to be involved in the genesis of the RBC phenotype.

Deformability was measured using two techniques that asses the response to different ranges of shear stresses acting on the cells: shape analysis of RBCs at low shear stress (0.1-3 Pa) (28) and real-time fluorescence and deformability cytometry (RT-FDC) (29,30) at high shear stress (ca. 100 Pa). The first only assesses the deformability of RBCs while RT-FDC was also used to characterize the mechanics of leukocytes. We demonstrate that the deformability of all blood cells is affected in ChAc patients and this is further modulated by the treatments. This highlights that monitoring blood cell mechanical properties of ChAc patients during the course of disease and possible treatments can increase our understanding of this disease.

2 Materials and Methods

2.1 Cell source and reagents

We included 5 ChAc patients in this study for whom diagnosis was confirmed by Western blot (absence of chorein/VPS13A protein) and genetic testing (31). The clinical parameters of the patients are listed in Table S1 and for P1-P3 further information can be found in Peikert et al., 2021 (19). Patients and healthy control blood donors were enrolled in ongoing studies on the pathogenesis and natural history of neurodegenerative diseases approved by the institutional review board of the Technische Universität Dresden, Germany (EK 45022009, EK 78022015). The ChAc patients were treated with dasatinib (P1-P3) or lithium (P4-P5) in the context of an individual off-label therapy based on the above described preclinical evidence. Standard dose of 100 mg dasatinib per day was administered orally, as it was lithium for which serum lithium concentration target range was defined as 0.6-0.8 mmol/l. Treatment started after the blood for the baseline measurements was taken.

2.2 RBC shape analysis at low shear stress

The distribution of shapes for RBCs flowing through a narrow capillary at a fixed flow condition is directly linked to the distribution of shear moduli within the population. Thus, changes in the shape distribution are directly linked to a change of cell mechanics in the sample. This approach and the experimental design are described in detail in Reichel et al., 2019 (28). Here, cells flow through a

roughly 5 mm long measurement channel that is 10-15 µm wide, and their shapes and dynamics are tracked at the end of the channel over a length of 435 µm. Cells were recorded with the same setup used for real-time deformability cytometry (29) using a different microfluidic chip. Examples of cells flowing through the region of interest are shown in figure 1A,B and in supplementary videos S1-S8.

The concepts introduced in Reichel et al., 2019 (28) cannot directly be used for samples containing acanthocytes because their shape at rest differs from that of healthy RBCs. Further, acanthocytes show shapes not observed for healthy cells (discocytes or normocytes) when deformed by the flow in the channel. For this study, cells flowing through a square channel with a width of 10 µm at cell velocities ranging up to 3 mm/s were characterized by their membrane morphology as normal looking (referred to as normocytes) or as acanthocytes if they showed thorn-like protrusions. Furthermore, cells were classified as either deformed by the flow or still maintaining their resting shape (undeformed). This classification was done by eye. A change of the cell mechanical properties should manifest in a change of the fraction of deformed cells in the sample and that the velocity at which the majority of RBCs get deformed is shifted to higher values.

For examples see figure 1A,B. The classification was done by eye from the recorded videos of cells passing the region of interest. This resulted in a curve with probabilities to find cells in a deformed state for a given range of velocities. The resulting curve for healthy RBCs is given in fig. 2A (data from Reichel et al., 2019 (28)). To characterize differences to ChAc patient cells and changes on the cells during treatment, a logistic growth function $A/(1+e^{-k(v-v_0)})$, with cell velocity v, was fitted to the data and the fit parameters A, v_0, and k were used to make statements of the progression of the curves during treatment (see fig 2A).

2.3 Real-time fluorescence and deformability cytometry (RT-FDC)

The setup of real-time fluorescence and deformability cytometry (RT-FDC) is described in detail in Otto et al., 2015 (29) and Rosendahl et al., 2018 (30). In brief, flow is introduced into a microfluidic chip with the help of syringe pumps and cells get deformed by hydrodynamic stresses as they pass a narrow constriction, still larger than their own size. The chip is mounted on an inverted microscope (Axiovert 200M, ZEISS, Oberkochen, Germany) and images are obtained at the end of the constriction with a CMOS camera (Mikrotron, Unterschleissheim, Germany). Camera and syringe pump are controlled via the measuring software ShapeIn (Zellmechanik Dresden, Dresden, Germany). ShapeIn analyzes the recorded images in real-time and computes a contour and projected area for each cell. The deformation parameter used in RT-FDC is defined as 1-circularity and is calculated from the contour's area and perimeter using: $\text{deformation} = 1 - 2 \cdot \sqrt{\pi \cdot \text{Area}}/\text{perimeter}$, illustrated on the example of a deformed RBC in figure 1C. As introduced by Toepfner et al., 2018 (32), the data from RT-FDC experiments can be used to distinguish between different types of blood cells. These strategies were used here to selectively study the deformation and mechanics of RBCs, lymphocytes, and myelocytes from ChAc patients (see also SI text).

Because the stresses required to deform RBCs are smaller than for leukocytes, both were measured under different conditions. For measurements on leukocytes, citrate blood was resuspended in a viscosity-adjusted measurement buffer (phosphate saline buffer without Mg^{2+} and Ca^{2+} (PBS−) containing 0.5% (w/v) methyl cellulose (4000 cPs, Alfa Aesar 036718.22, CAS# 9004-67-5); adjusted in HAAKE Falling Ball Viscometer type C (Thermo Fisher Scientific, Dreieich, Germany) using ball number 3 to a viscosity of 15 mPa s) at a ratio of 1:20. The increased viscosity of the buffer also increases the stresses acting on the cells inside the channel. Measurements were performed in channels with 20×20 µm cross-section at a flow rate of 0.08 µl/s. Example images of a deformed lymphocyte

152 and myelocyte are shown in figure 1D and E, respectively. To decouple effects of the cell size on the
153 deformation, the Young's modulus was computed for leukocytes as described in Mokbel et al., 2017
154 (33). Since the derivation of Young's moduli for this system is only valid for initially spherical cells
155 (33,34), it cannot be calculated for RBCs.

156 RBC measurements were performed on an RT-FDC setup with a fluorescence module described in
157 detail in Rosendahl et al., 2018 (30). Whole blood was resuspended in the same measurement buffer
158 described above at a ratio of 1:200. The buffer was complemented with 2.5 µM syto13 nucleic acid
159 stain (Thermo Fisher Scientific, Dreieich, Germany) to mark for the reticulocytes in the sample.
160 Fluorescence was excited with a 60 mW, 488 nm laser at 8 % power (OBIS 488-nm LS 60 mW,
161 Coherent Deutschland) and the signal was measured with an avalanche photodiode (MiniSM10035;
162 SensL Corporate, Cork, Ireland). Measurements were performed in channels with a 20×20 µm cross-
163 section at a flow rate of 0.02 µl/s.

164 **2.4 Data analysis and data availability**

165 Data was analyzed and plotted using custom python scripts. For details, see SI text.

166 The raw experiment data is available in the deformability cytometry open repository, DCOR, under
167 https://dcor.mpl.mpg.de. Scripts used to analyze the data are available in the supplementary material
168 or by request to the authors.

169 **3 Results**

170 **3.1 Red blood cell deformability in Chorea-Acanthocytosis**

171 To investigate differences in the deformability of red blood cells (RBCs) from chorea-acanthocytosis
172 (ChAc) patients compared to that of healthy donors, we performed shape-analysis and real-time
173 fluorescence and deformability cytometry (RT-FDC) measurements on the blood of 5 patients (P1-P5)
174 and compared it with measurements of healthy controls. The results are depicted in figure 1A,B and
175 1F,G. Every velocity bin of 0.25 mm/s in figure 1A and B includes approx. 100 cells for each patient.
176 The shape-probability curves of normocytes (fig. 1A) and acanthocytes (fig. 1B) show that RBCs from
177 ChAc patients are less likely to deform in channel flow. It should be mentioned that also control
178 samples can include acanthocyte-like cells but to a much lesser extent than in patient samples.
179 Acanthocytes are clearly less likely to deform due to flow even for higher flow velocities.

180 The RT-FDC measurements show that the RBCs of ChAc patients have a slightly larger projected area
181 than those from healthy donors (fig. 1F, effect size of +1.89 μm^2, p=0.0036 computed with linear mixed
182 effect models (35)). No significant difference between control and ChAc RBCs' deformation could be
183 detected (p=0.1382, fig. 1G).

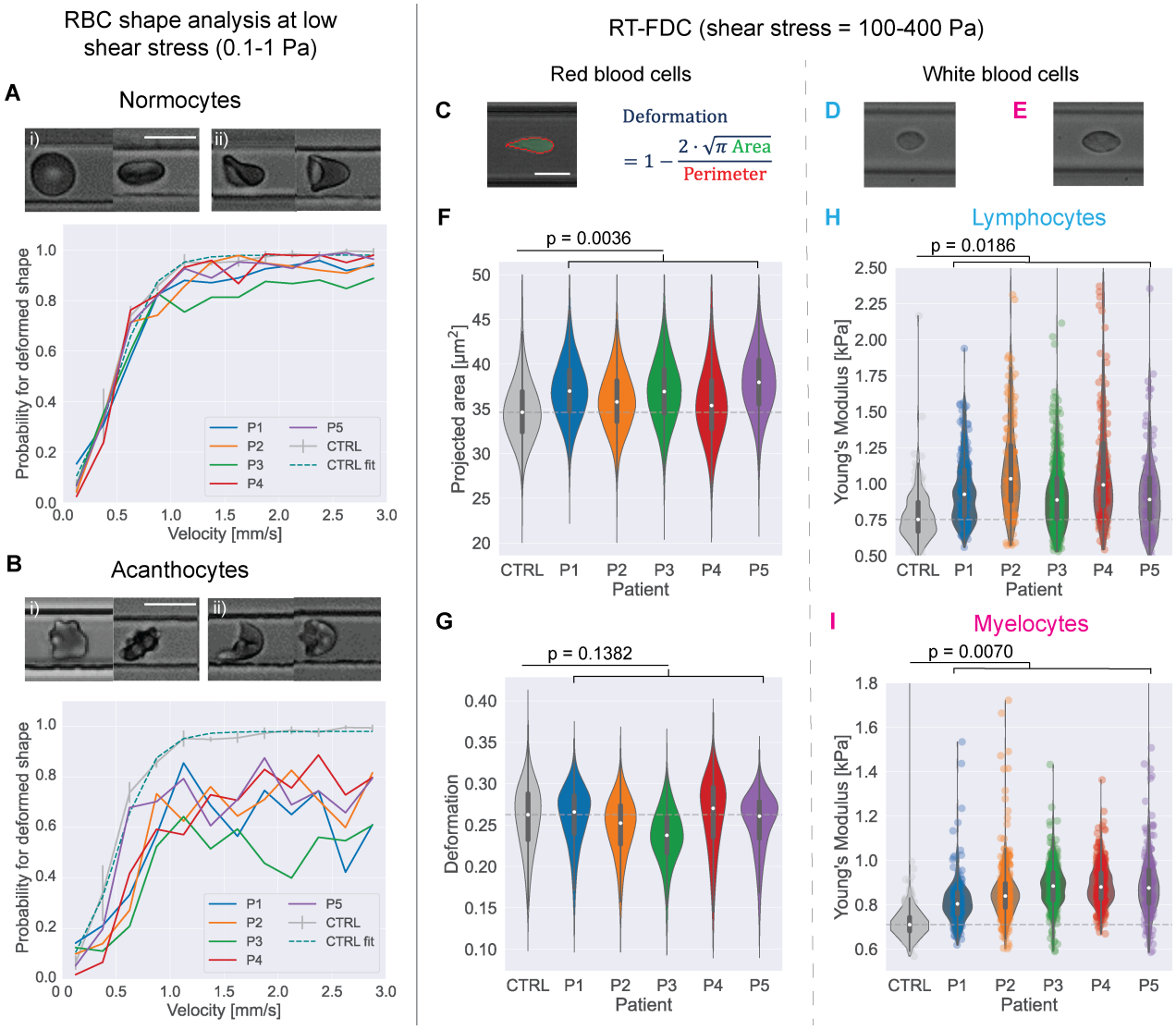

Figure 1: Blood cell deformability of ChAc patients compared to healthy control blood. (A) Example shapes of normal, discocyte RBCs (normocytes) in an **(i)** undeformed state and **(ii)** deformed by flow during low shear stress flow in a 10 µm channel. The diagram shows the probability to find normocyte cells from the sample in a deformed state at a given cell velocity in the channel for the acanthocyte patients and the mean curve from 3 control measurements. Error bars represent SEM. Dotted line shows a logistic-growth function fit to the control data (see fig. 2A) **(B)** Example shapes of acanthocytes in an **(i)** undeformed state and **(ii)** deformed by flow. Below is the shape probability diagram for the acanthocytes and the control curves. **(C)** Example shape of an RBC in RT-FDC and representation how the deformation parameter is computed. All scale bars represent 10 µm. **(D)** Example image of a lymphocyte in RT-FDC. **(E)** Example image of a myelocyte. **(F)**, **(G)** Projected area within the contour and deformation of RBCs of the ChAc patients from RT-FDC measurements vs. pooled data from 10 control measurements (full data in fig. S4). White dots represent the median value; grey box in the violin shows inter-quartile range (IQR) and extended lines 1.5×IQR. Dashed grey line shows the median control value. P-values were calculated with linear-mixed effect models as described in Herbig et al., 2018 (35). **(H)** Young's modulus of lymphocytes from ChAc patients vs. control. **(I)** Young's modulus of myelocytes from ChAc patients vs. control.

201 **3.2 White blood cell deformability in Chorea-Acanthocytosis**

202 In RT-FDC measurements on whole blood it is possible to distinguish different cell types (see materials
203 and methods, SI text and Töpfner et al., 2018 (32)). Thus, we investigated mechanical differences also
204 between the leukocytes of ChAc patients and healthy donors. We distinguish, mainly by size, between
205 all lymphocytes and cells resulting from the myeloid lineage (myelocytes), comprising all mono- and
206 granulocytes. The myelocyte fraction mainly consists of neutrophil granulocytes (> 80%).

207 Since white blood cells are spherical at rest, we can employ a model that correlates the projected area
208 and the deformation to an apparent Young's modulus (33), to see differences in stiffness before, during
209 and after the treatments. It can be seen (fig. 1H,I) that both lymphocytes and myelocytes of ChAc
210 patients are significantly stiffer than their healthy counterparts before treatment onset (lymphocytes:
211 +240 Pa, p=0.0186, myelocytes: +150 Pa, p=0.0070; effect sizes and p-values determined by linear
212 mixed effects model analysis (35)).

213 **3.3 Dasatinib and lithium treatment effect on RBC deformability**

214 **3.3.1 RBC shape analysis during dasatinib or lithium treatment**

215 To study the effect of dasatinib or lithium on RBC deformability of ChAc patients, we monitored RBCs
216 during treatment with shape analysis measurements and RT-FDC.

217 To compare shape-analysis data over the treatment time, a logistic-growth function was fitted to the
218 data (see fig. 2A) and the fitting parameters were used to detect changes in the deformability during
219 the treatment time. The results for the dasatinib treatment are shown in figure 2B-D. The lithium results
220 are depicted in figure 3. The plateauing probability A (fig. 2B) for normocytes and acanthocytes
221 increases slightly during treatment with dasatinib and drops again after treatment. The parameter
222 estimates the probability of deformed cells at very high velocities ($v \to \infty$) and is close to 100% for
223 control blood, meaning nearly all RBCs should deform at high velocities. This indicates that RBCs
224 become more deformable during dasatinib treatment. The results for the other fitting parameters do not
225 show a clear trend. The results pooled for all cells are shown in figure S1 and the curves from all
226 measurements are given in figure S2.

227 The acanthocyte count over the treatment is given in figure 2E and shows that the fraction of
228 acanthocytes remains constant within a certain range of fluctuation without a systematic trend for both
229 treatments, which is in line with the clinical data (19).

230 To check if dasatinib has a short-term effect on RBC deformability, RBCs from P3 were treated with
231 dasatinib *in vitro* and the shapes in channel flow were analyzed (for details, see SI text). The results
232 are shown in figure 2F. There was no significant difference in the deformability between control- and
233 dasatinib-treated RBCs. This indicates that the observed effects on cell deformability are likely caused
234 by long-term treatment effects, e.g., acting on erythropoiesis or indirect systemic effects.

235 During treatment with lithium, we also observed an apparent increase of the plateauing probability
236 with and even after treatment time for normocytes and acanthocytes (fig. 3A). Transition velocity (fig.
237 3B) and growth rate (fig. 3C) both decreased with treatment time, but the scarcity of the datapoints
238 makes it difficult to draw any conclusions from these results.

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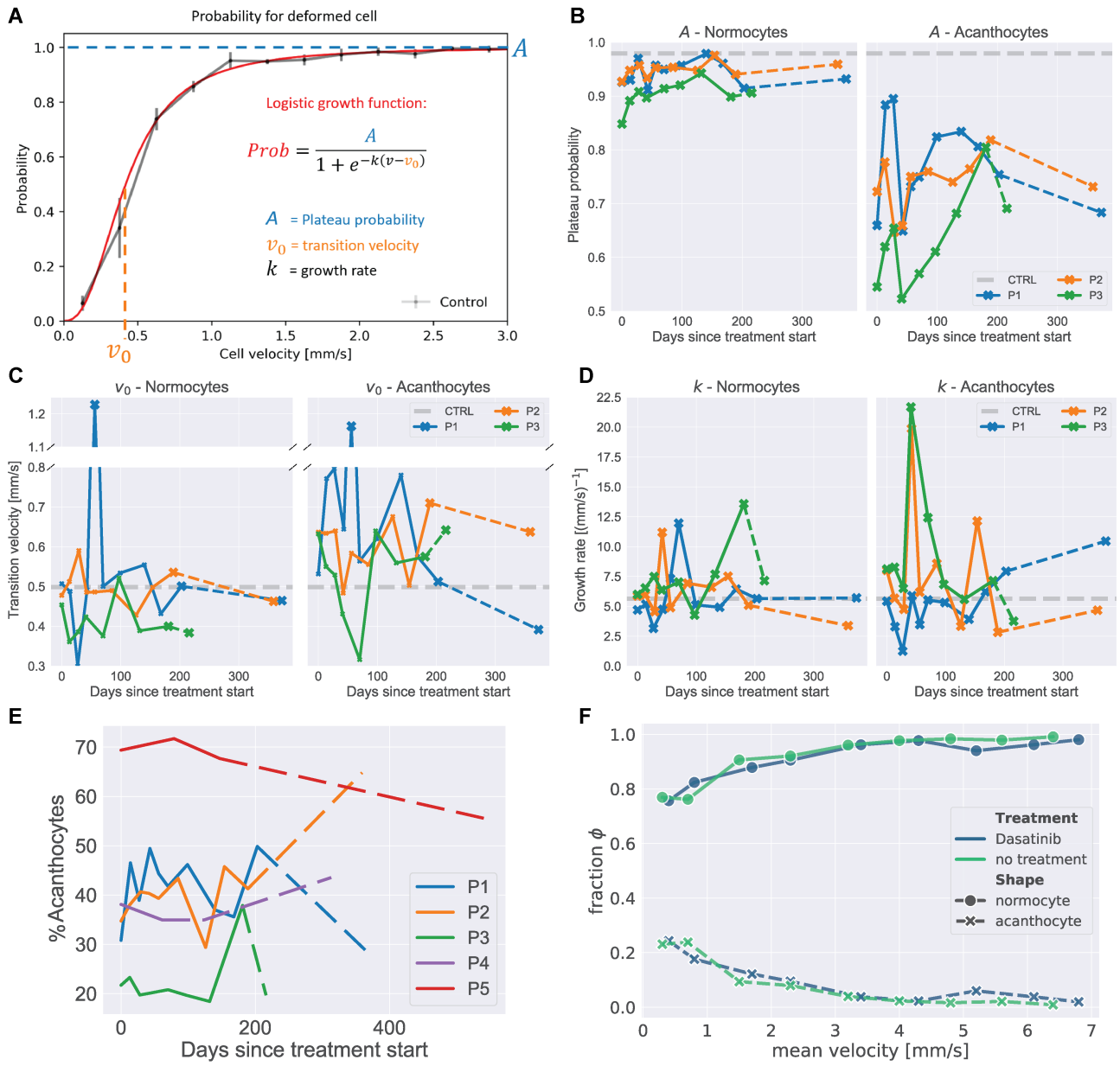

Figure 2: Dasatinib treatment effect on RBC deformability. (A) Illustration of the fitting parameters used to characterize the shape probability curves presented on the control data. **(B)** Fitted plateauing probability A of the shape probability curves from ChAc patients as a function of treatment time with dasatinib for normocytes and acanthocytes respectively. Dashed lines represent datapoints taken after treatment was stopped. Dashed grey lines show the respective value from healthy donors without treatment. **(C)** Fitted transition velocity v_0 for the probability to find deformed cells over treatment time. **(D)** Fitted growth rate k of the probability over treatment time. **(E)** Percentage of acanthocytes found in each sample during shape analysis measurements for patients P1-P5. Dashed lines indicate datapoints taken after the respective treatment already stopped. **(F)** Fraction of healthy shapes (hs) and acanthocytes (ac) over cell velocity for untreated and *in-vitro* dasatinib treated RBCs from patient P3.

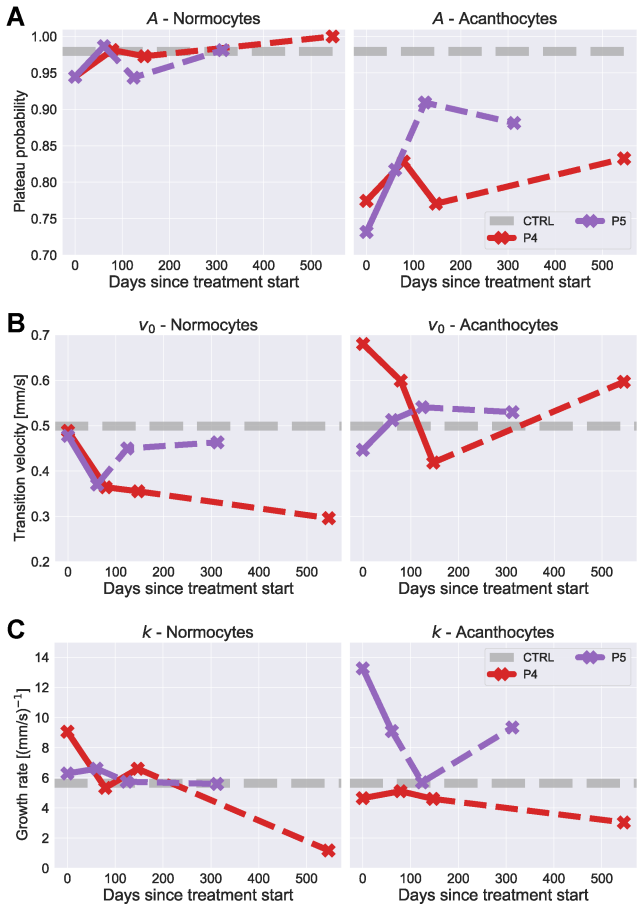

Figure 3: Lithium treatment effect on RBC deformability. (one column figure) **(A)** Fitted plateauing probability A of the shape probability curves from ChAc patients as a function of treatment time with lithium for normocytes and acanthocytes respectively. Dashed lines represent datapoints taken after treatment was stopped. Dashed grey lines show the respective value from healthy donors without treatment. **(B)** Fitted transition velocity v_0 for the probability to find deformed cells over treatment time. **(C)** Fitted growth rate k of the probability over treatment time.

3.3.2 RBC deformation in RT-FDC during dasatinib or lithium treatment

RT-FDC results for the dasatinib treatment are shown in figure 4A-C and for the lithium treatment in figure 4D-F. It can be seen that during treatment with dasatinib, the RBC deformation parameter drops for all patients between 50-100 days after treatment start, while the projected area remains mainly constant with the exception of some outliers.

For the lithium treatment, the RT-FDC results show that the deformation parameter decreases with treatment time which is accompanied by an increase in cell size. After the treatment, the deformation and area values return almost to the control values for P5 while the values for P4 do not fully recover.

The interpretation of deformation values for RBCs in RT-FDC cannot directly be linked to cell mechanics because they undergo a non-trivial shape transition from discocyte to tear-drop shape (28). A decrease of the deformation value does not necessarily mean that the cells got stiffer. To back this up, we artificially stiffened RBCs from healthy donors with glutaraldehyde (36,37) or diamide (38) (see SI text and fig. S3) and saw that an increasing concentration of the reagents led to an increase of the deformation when working at low concentrations. At high concentrations the cell shape gets fixed which leads to lower deformation values.

Since reticulocytes have been reported to have a higher projected area and lower deformation compared to the whole RBC population (30), we speculated that above mentioned results might be due to increased levels of reticulocytes in ChAc patients. The results for reticulocytes, labelled with syto13 nucleic acid stain, together with all RBCs are given in figure S4A-D. The patients' reticulocytes indeed

had higher projected area and lower deformation if compared to the whole RBC population which did not differ from healthy controls. Qualitatively, reticulocyte area and deformation change over treatment time like the total RBC population. The fraction of reticulocytes in the blood is initially higher compared to controls and slightly decreases during the dasatinib treatment closer to values from healthy donors (fig. 4C). A reduction of the reticulocyte count with dasatinib treatment was also reported for VPS13a$^{-/-}$ mice phenocopying human ChAc (18). During lithium treatment P5 showed a decrease during and after treatment, while P4 showed a slight increase but values were mostly in the range expected for healthy individuals (0.5-2.5%).

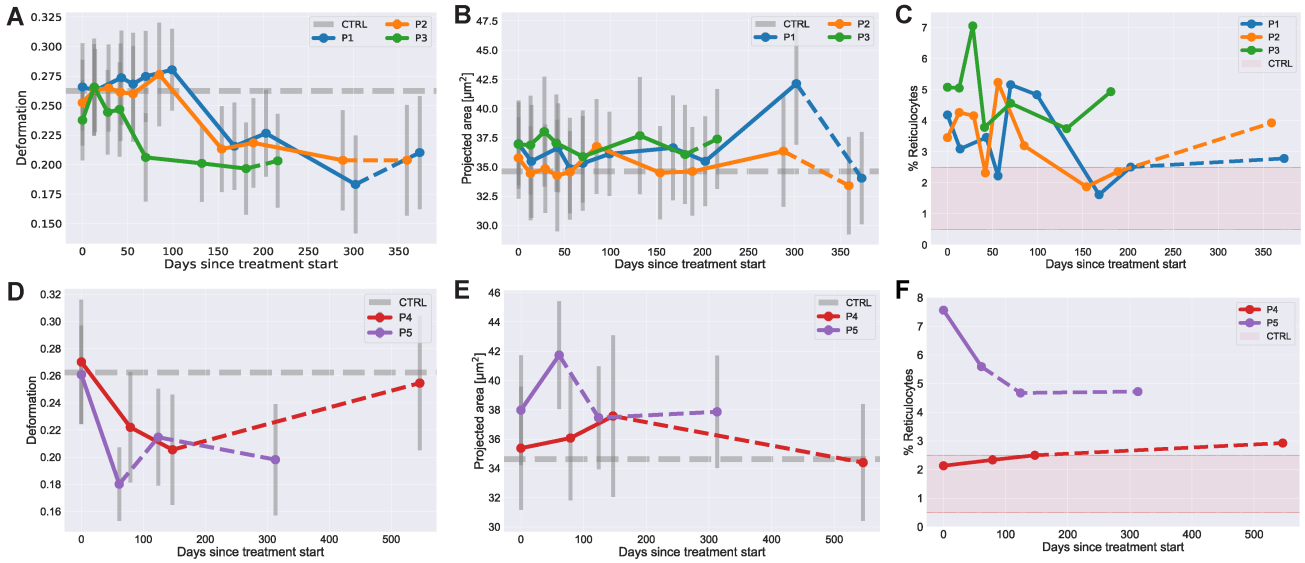

Figure 4: RBC deformation, size and reticulocyte count in RT-FDC during treatment with Dasatinib or lithium. (A-C) RBC median deformation, projected area and reticulocyte fraction measured with RT-FDC before, during and after treatment with dasatinib. **(D-F)** RBC median deformation, projected area and reticulocyte fraction measured with RT-FDC before, during and after treatment with lithium. Dashed lines indicate time points after the treatment was stopped, dashed gray lines indicate control values without treatment. The red region in the reticulocyte plots indicates the range for healthy individuals reported in the literature of 0.5-2.5%.

3.4 ChAc Leukocytes stiffen during treatment with dasatinib

The Young's moduli of lymphocytes and myelocytes in dasatinib treatment are shown in figure 5A,B. The lithium data is shown in figure 5C,D. During treatment with dasatinib, we observe a further increase of the Young's modulus for all three patients which also persists for the lymphocytes shortly after the treatment stopped. For myelocytes, the median Young's modulus decreases for patients P1 and P2 shortly after the treatment but keeps increasing for P3.

During treatment with lithium both patients show an increase in lymphocyte and myelocyte stiffness. After the treatment stopped, we observe a further increase for patient P4 and a drop back to the pre-treatment level for patient P5 approximately one year after the treatment stopped. The area and deformation data used to compute the Young's modulus is given in figure S5C,D.

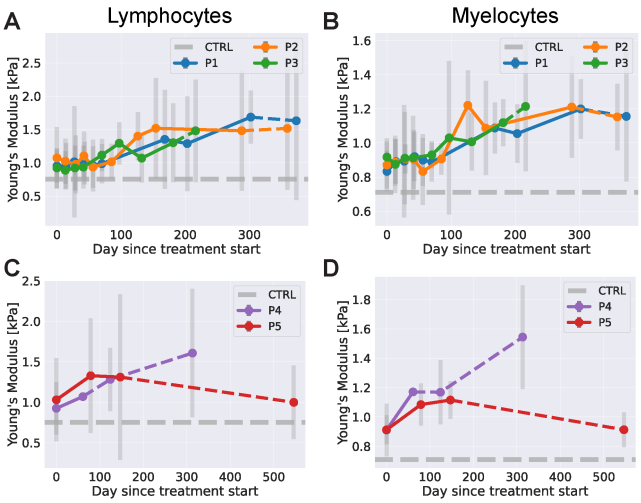

Figure 5: Leukocyte stiffness in RT-FDC during treatment with Dasatinib or lithium. (one column figure) **(A)** Median Young's modulus of ChAc patients' lymphocytes during dasatinib treatment. **(B)** Median Young's modulus of ChAc patients' myelocytes during dasatinib treatment. **(C)** Median Young's modulus of ChAc patients' lymphocytes during lithium treatment. **(D)** Median Young's modulus of ChAc patients' myelocytes during lithium treatment.

4 Discussion

Our study highlights that the deformability, not only of RBCs, but of all blood cell types was altered in ChAc patients. Shape analysis results hinted at a decreased deformability of ChAc RBCs compared to controls. The decreased deformability can be directly inferred from the reduced number of deformed cells at any cell velocity. A reduced deformability of ChAc RBCs, deduced from cell shapes, has recently also been reported by Rabe et al., 2021 (39).

In RT-FDC, we did not observe a change in the deformation parameter but ChAc RBCs had a bigger projected area. Because deformation and size are always correlated in RT-FDC (34), this is also an indicator for a change of RBC deformability, but the interpretation of this behavior is not straight forward. To see how the deformation parameter changes when RBC stiffness is controllably changed, we treated RBCs *in vitro* with glutaraldehyde or diamide. At low concentrations, we observed an increase of the deformation parameter which shows that higher deformation parameter can also occur for stiffer RBCs.

While we observed bigger RBCs in ChAc patients, values for the mean corpuscular volume (MCV) reported in Peikert et al., 2021 (19) did not show an increased RBC volume for patients P1-P3. Sizes reported in RT-FDC measurements are based on the projected cross-sectional area of the deformed cells. Simulations of the flow fields inside the channel suggest that the stresses near the centerline can be approximated as axisymmetric (40). Therefore, it is fair to assume that the RBCs take up an axisymmetric shape as well and the projected area is directly correlated to cell size. In automated cell counters, the MCV is determined, e.g., by impedance or light scattering measurements which require a constant deformability of RBCs for a reliable result. So, MCV is not a direct measurement of single cell sizes. Here, we provide a direct observation of sizes based on single cell imaging.

Shape analysis and RT-FDC both indicated a change of RBC deformability during treatment with dasatinib. Shape analysis experiments showed an increase of the plateau probability parameter with treatment time, which showed that more deformed cells are observed at high cell velocities, hinting at an increased deformability of both normocytes and acanthocytes. In RT-FDC, we observed a sharp drop of the deformation parameter after 50-100 treatment days while the size fluctuated around a constant value. Again, for RBCs a direct link between the deformation parameter in RT-FDC and cell mechanics is not trivial and a decrease in deformation does not necessarily mean that the cells got

361 stiffer (see fig. S3). Even though we do not have certainty of the direction of the change, we claim that
362 RBC mechanics was altered during dasatinib treatment.

363 The sharp drop in deformation for the RBCs occurred at different timepoints for P3 than for P1 and
364 P2. A possible correlation to this can be found in the levels of Lyn kinase and the autophagy marker
365 p62 for the patients reported in Peikert et al., 2021 (19). Lyn kinase levels for P3 dropped directly after
366 treatment start and stayed on this level during the treatment while the levels for P1 and P2 had a sudden
367 rise after 10 weeks of treatment. On the other hand, the levels of p62 stayed rather constant for P1 and
368 P2 during the treatment while they were rising above control level for P3 after 10 weeks. Patient
369 incompliance during treatment could be a possible explanation for these effects.

370 During lithium treatment, we also observed an increasing plateauing probability in the shape analysis
371 accompanied with a decrease of the transition velocity, both indicators for increased RBC
372 deformability. In RT-FDC we saw a decrease of deformation accompanied by an increase in projected
373 area. An increase in projected area and decrease in deformation hints at a volume increase and a
374 reduced surface area-to-volume ratio, which leads to an increased sphericity or effective rounding of
375 the cells. Rounder shapes lead to smaller deformation values, assuming that this effect dominates any
376 stiffness changes of the cells. All in all, these findings indicate that lithium affects RBC properties in
377 ChAc patients but because of the scarcity of the data here, one should be careful with the interpretation.

378 Data from Peikert et al., 2021 indicated that with 12asatinib treatment, F-actin became more localized
379 at the cortex (19). These modifications in the actin network likely contribute to changes in RBC
380 deformability (41) that we observed here.

381 Treatment with dasatinib led to a decrease of the reticulocyte fraction in the blood of ChAc patients.
382 The same effect was observed in a mouse model phenocopying human ChAc (18). Peikert et al., 2021
383 report an abundance of the autophagy initiator Ulk1 in ChAc patients RBCs, which decreased with
384 dasatinib treatment (19). Ulk1 is connected to autophagy in erythropoiesis and could influence the rate
385 of reticulocyte production (42), providing a mechanistic link to the reticulocyte count.

386 While an impaired RBC deformability was described before for patients with other forms of
387 neuroacanthocytosis (43) this is, to our knowledge, the first time that also patients' leukocyte stiffness
388 was studied. Lymphocytes and myelocytes were both stiffer in ChAc patients compared to cells from
389 healthy donors. This is of interest as VPS13A, the gene which is known to have a loss-of-function
390 mutation in ChAc, is especially expressed in human monocytes and B-, and helper T-cells (44). Since
391 VPS13A is known to cause structural reorganizations of the cytoskeleton from studies on other cell
392 types (17,20,45), it is likely that we observed these as altered mechanical properties in leukocytes.
393 Another feature in ChAc blood is an increased expression of Lyn kinase, which is known to set the
394 threshold for B-cell activation. Mechanical changes of lymphocytes after activation have been reported
395 before (32,46). Another mechanism that could lead to altered leukocyte mechanics is an increase in
396 interleukin-1 beta (IL-1b) that was observed in the brain of Vps13a knockout mice (18). IL-1b not only
397 plays a key role in autoinflammation but is also known to cause re-organization of the actin
398 cytoskeleton in different cell types (47,48).

399 Young's moduli of both lymphocytes and myelocytes increased even further away from control values
400 during treatment with dasatinib or lithium. A stiffening was previously also observed for leukemic cells
401 during treatment with different chemotherapeutic agents for acute lymphoblastic leukemia
402 (dexamethasone and daunorubicin), such as dasatinib (49). Dasatinib interferes with all the pathways
403 described above and likely induces further mechanical changes in leukocytes. The inhibited activity of

Lyn during dasatinib treatment could cause a change in lymphocyte activation levels leading to altered mechanics but the exact mechanisms for the observed leukocyte stiffening with dasatinib treatment remain rather speculative at this point.

Overall, our results show that the mechanical phenotype of all blood cell types in ChAc patients were impaired but did not change towards regimes of healthy donors during the treatments. This demonstrates that the techniques that were utilized here are suited to measure a treatment response. Clinical data in Peikert et al., 2021 (19) hints on slightly improved hematological features but these did not manifest in an improved neurological phenotype.

In general, decreased blood cell deformability often leads to clinical symptoms due to decreased cell survival and secondary pathology (25–27,50). Especially, an impaired oxygen transport by altered blood cell deformability should be considered in neurological diseases (51). While clinical descriptions of ChAc patients focus on neurological symptoms, we highlight in this study that the effects on blood deformability should not be neglected and could contribute to the clinical manifestation (through the mechanisms stated above) and thus methods that are able to monitor this (as shown here) should be considered as read outs for clinical trials. Our results on the impaired mechanics of leucocytes especially highlights that the focus of ChAc research should not only be on RBCs but also include other blood cell types.

5 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 Author Contributions

Conceptualization: F.R., M.K., K.P., G.B., A.H., and J.G.; Experiments–shape analysis: F.R. and A.R.P., Experiments–RT-FDC: F.R., P.R., M.H., and M.K., Experiments–in-vitro shape analysis: A.K.; Formal analysis: F.R., P.R., A.K., and M.K.; Supervision: L.K.,A.H., and J.G.; Writing–original draft, K.P. and F.R..; Writing–review and editing, F.R., M.K., K.P., G.B., L.K., A.H., and J.G.; All authors have read and agreed to the published version of the manuscript.

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9 Supplementary Material

Supplementary Information, Figures, Table and Videos will be available online.

10 Data Availability statement

The raw experiment data is available in the deformability cytometry open repository, DCOR, under https://dcor.mpl.mpg.de. Scripts used to analyze the data are available in the supplementary material or by request to the authors.

11 References

1. Jung HH, Danek A, Walker RH. Neuroacanthocytosis Syndromes. Orphanet J Rare Dis. (2011) 6(1):68. doi: 10.1186/1750-1172-6-68

2. Peikert K, Danek A, Hermann A. Current state of knowledge in Chorea-Acanthocytosis as core Neuroacanthocytosis syndrome. Eur J Med Genet. (2018) 61(11):699–705. doi: 10.1016/j.ejmg.2017.12.007

3. Walker RH. Chorea-Acanthocytosis. In: Reference Module in Neuroscience and Biobehavioral Psychology. Elsevier; (2017.). doi: 10.1016/B978-0-12-809324-5.00521-6

4. Levine IM, Estes JW, Looney JM. Hereditary Neurological Disease With Acanthocytosis: A New Syndrome. Arch Neurol. (1968) 19(4):403–9. doi: 10.1001/archneur.1968.00480040069007

5. Critchley EMR, Clark DB, Wikler A. Acanthocytosis Without. Arch Neurol. (1968) 18(2):134–40. doi: 10.1001/archneur.1968.00470320036004

6. Danek A, Bader B, Velayos-Baeza A, Walker RH. Autosomal recessive transmission of chorea-acanthocytosis confirmed. Acta Neuropathol. (2012) 123(6):905–6. doi: 10.1007/s00401-012-0971-y

7. Dobson-Stone C, Danek A, Rampoldi L, Hardie R, Chalmers R, Wood N, et al. Mutational spectrum of the CHAC gene in patients with chorea-acanthocytosis. Eur J Hum Genet. (2002) 10(11):773–81. doi: 10.1038/sj.ejhg.5200866

8. Rampoldi L, Dobson-Stone C, Rubio JP, Danek A, Chalmers RM, Wood NW, et al. A conserved sorting-associated protein is mutant in chorea-acanthocytosis. Nat Genet. (2001) 28(2):119–20. doi: 10.1038/88821

476 9. Ueno S, Maruki Y, Nakamura M, Tomemori Y, Kamae K, Tanabe H, et al. The gene encoding
477 a newly discovered protein, chorein, is mutated in chorea-acanthocytosis. Nat Genet. (2001)
478 28(2):121–2. doi: 10.1038/88825

479 10. Nishida Y, Nakamura M, Urata Y, Kasamo K, Hiwatashi H, Yokoyama I, et al. Novel
480 pathogenic VPS13A gene mutations in Japanese patients with chorea-acanthocytosis. Neurol
481 Genet. (2019) 5(3):e332. doi: 10.1212/NXG.0000000000000332

482 11. Walker RH, Danek A. "Neuroacanthocytosis" – Overdue for a Taxonomic Update. Tremor
483 and Other Hyperkinetic Movements. (2021) 11(1):1–6. doi: 10.5334/tohm.583

484 12. Leonzino M, Reinisch KM, De Camilli P. Insights into VPS13 properties and function reveal a
485 new mechanism of eukaryotic lipid transport. Biochim Biophys Acta - Mol Cell Biol Lipids.
486 (2021) 1866(10):159003. doi: 10.1016/j.bbalip.2021.159003

487 13. Gao M, Yang H. VPS13: A lipid transfer protein making contacts at multiple cellular
488 locations. J Cell Biol. (2018) 217(10):3322–4. doi: 10.1083/jcb.201808151

489 14. Kumar N, Leonzino M, Hancock-Cerutti W, Horenkamp FA, Li P, Lees JA, et al. VPS13A
490 and VPS13C are lipid transport proteins differentially localized at ER contact sites. J Cell Biol.
491 (2018) 217(10):3625–39. doi: 10.1083/jcb.201807019

492 15. Yeshaw WM, van der Zwaag M, Pinto F, Lahaye LL, Faber AIE, Gómez-Sánchez R, et al.
493 Human VPS13A is associated with multiple organelles and influences mitochondrial
494 morphology and lipid droplet motility. Elife. (2019) 8. doi: 10.7554/eLife.43561

495 16. Lupo F, Tibaldi E, Matte A, Sharma AK, Brunati AM, Alper SL, et al. A new molecular link
496 between defective autophagy and erythroid abnormalities in chorea-acanthocytosis. Blood.
497 (2016) 128(25):2976–87. doi: 10.1182/blood-2016-07-727321

498 17. De Franceschi L, Tomelleri C, Matte A, Brunati AM, Bovee-Geurts PH, Bertoldi M, et al.
499 Erythrocyte membrane changes of chorea-acanthocytosis are the result of altered Lyn kinase
500 activity. Blood. (2011) 118(20):5652–63. doi: 10.1182/blood-2011-05-355339

501 18. Peikert K, Federti E, Matte A, Constantin G, Pietronigro EC, Fabene PF, et al. Therapeutic
502 targeting of Lyn kinase to treat chorea-acanthocytosis. Acta Neuropathol Commun. (2021)
503 9(1):81. doi: 10.1186/s40478-021-01181-y

504 19. Peikert K, Glaß H, Federti E, Matte A, Pelzl L, Akgün K, et al. Targeting Lyn Kinase in
505 Chorea-Acanthocytosis: A Translational Treatment Approach in a Rare Disease. J Pers Med.
506 (2021) 11(5):392. doi: 10.3390/jpm11050392

507 20. Föller M, Hermann A, Gu S, Alesutan I, Qadri SM, Borst O, et al. Chorein-sensitive
508 polymerization of cortical actin and suicidal cell death in chorea-acanthocytosis. FASEB J.
509 (2012) 26(4):1526–34. doi: 10.1096/fj.11-198317

510 21. Pelzl L, Elsir B, Sahu I, Bissinger R, Singh Y, Sukkar B, et al. Lithium Sensitivity of Store
511 Operated Ca2+ Entry and Survival of Fibroblasts Isolated from Chorea-Acanthocytosis
512 Patients. Cell Physiol Biochem. (2017) 42(5):2066–77. doi: 10.1159/000479901

513 22. Pelzl L, Hauser S, Elsir B, Sukkar B, Sahu I, Singh Y, et al. Lithium Sensitive ORAI1
514 Expression, Store Operated Ca2+ Entry and Suicidal Death of Neurons in Chorea-
515 Acanthocytosis. Sci Rep. (2017) 7(1):6457. doi: 10.1038/s41598-017-06451-1

516 23. Yu W, Honisch S, Schmidt S, Yan J, Schmid E, Alkahtani S, et al. Chorein Sensitive Orai1
517 Expression and Store Operated Ca2+ Entry in Rhabdomyosarcoma Cells. Cell Physiol
518 Biochem. (2016) 40(5):1141–52. doi: 10.1159/000453168

519 24. Rampoldi L, Danek A, Monaco AP. Clinical features and molecular bases of
520 neuroacanthocytosis. J Mol Med. (2002) 80(8):475–91. doi: 10.1007/s00109-002-0349-z

521 25. Adjobo-Hermans MJW, Cluitmans JCA, Bosman GJCGM. Neuroacanthocytosis:
522 Observations, Theories and Perspectives on the Origin and Significance of Acanthocytes.
523 Tremor and Other Hyperkinetic Movements. (2015) 5:328. doi: 10.5334/tohm.271

524 26. An X, Mohandas N. Disorders of red cell membrane. Br J Haematol. (2008) 141:367–75. doi:
525 10.1111/j.1365-2141.2008.07091.x

526 27. Da Costa L, Galimand J, Fenneteau O, Mohandas N. Hereditary spherocytosis, elliptocytosis,
527 and other red cell membrane disorders. Blood Rev. (2013) 27(4):167–78. doi:
528 10.1016/j.blre.2013.04.003

529 28. Reichel F, Mauer J, Nawaz AA, Gompper G, Guck J, Fedosov DA. High-Throughput
530 Microfluidic Characterization of Erythrocyte Shapes and Mechanical Variability. Biophys J.
531 (2019) 117(1):14–24. doi: 10.1016/j.bpj.2019.05.022

532 29. Otto O, Rosendahl P, Mietke A, Golfier S, Herold C, Klaue D, et al. Real-time deformability
533 cytometry: on-the-fly cell mechanical phenotyping. Nat Methods. (2015) 12(3):199–202. doi:
534 10.1038/nmeth.3281

535 30. Rosendahl P, Plak K, Jacobi A, Kraeter M, Toepfner N, Otto O, et al. Real-time fluorescence
536 and deformability cytometry. Nat Methods. (2018) 15(5):355–8. doi: 10.1038/nmeth.4639

537 31. Dobson-Stone C, Velayos-Baeza A, Filippone LA, Westbury S, Storch A, Erdmann T, et al.
538 Chorein detection for the diagnosis of chorea-acanthocytosis. Ann Neurol. (2004) 56(2):299–
539 302. doi: 10.1002/ana.20200

540 32. Toepfner N, Herold C, Otto O, Rosendahl P, Jacobi A, Kräter M, et al. Detection of human
541 disease conditions by single-cell morpho-rheological phenotyping of blood. Elife. (2018)
542 7:e29213. doi: 10.7554/eLife.29213

543 33. Mokbel M, Mokbel D, Mietke A, Träber N, Girardo S, Otto O, et al. Numerical Simulation of
544 Real-Time Deformability Cytometry To Extract Cell Mechanical Properties. ACS Biomater
545 Sci Eng. (2017) 3(11):2962–73. doi: 10.1021/acsbiomaterials.6b00558

546 34. Mietke A, Otto O, Girardo S, Rosendahl P, Taubenberger A, Golfier S, et al. Extracting Cell
547 Stiffness from Real-Time Deformability Cytometry: Theory and Experiment. Biophys J.
548 (2015) 109(10):2023–36. doi: 10.1016/j.bpj.2015.09.006

549 35. Herbig M, Mietke A, Müller P, Otto O. Statistics for real-time deformability cytometry:

550 Clustering, dimensionality reduction, and significance testing. Biomicrofluidics. (2018)
551 12(4):042214. doi: 10.1063/1.5027197

552 36. Holmes D, Whyte G, Bailey J, Vergara-Irigaray N, Ekpenyong A, Guck J, et al. Separation of
553 blood cells with differing deformability using deterministic lateral displacement. Interface
554 Focus. (2014) 4(6):20140011. doi: 10.1098/rsfs.2014.0011

555 37. Forsyth AM, Wan J, Ristenpart WD, Stone HA. The dynamic behavior of chemically
556 "stiffened" red blood cells in microchannel flows. Microvasc Res. (2010) 80(1):37–43. doi:
557 10.1016/j.mvr.2010.03.008

558 38. Sinha A, Chu TTT, Dao M, Chandramohanadas R. Single-cell evaluation of red blood cell bio-
559 mechanical and nano-structural alterations upon chemically induced oxidative stress. Sci Rep.
560 (2015) 5(1):9768. doi: 10.1038/srep09768

561 39. Rabe A, Kihm A, Darras A, Peikert K, Simionato G, Dasanna AK, et al. The Erythrocyte
562 Sedimentation Rate and Its Relation to Cell Shape and Rigidity of Red Blood Cells from
563 Chorea-Acanthocytosis Patients in an Off-Label Treatment with Dasatinib. Biomolecules.
564 (2021) 11(5):727. doi: 10.3390/biom11050727

565 40. Panhwar MH, Czerwinski F, Dabbiru VAS, Komaragiri Y, Fregin B, Biedenweg D, et al.
566 High-throughput cell and spheroid mechanics in virtual fluidic channels. Nat Commun. (2020)
567 11(1):2190. doi: 10.1038/s41467-020-15813-9

568 41. Gokhin DS, Nowak RB, Khoory JA, Piedra A de la, Ghiran IC, Fowler VM. Dynamic actin
569 filaments control the mechanical behavior of the human red blood cell membrane. Pollard TD,
570 editor. Mol Biol Cell. (2015) 26(9):1699–710. doi: 10.1091/mbc.E14-12-1583

571 42. Kundu M, Lindsten T, Yang C-Y, Wu J, Zhao F, Zhang J, et al. Ulk1 plays a critical role in
572 the autophagic clearance of mitochondria and ribosomes during reticulocyte maturation.
573 Blood. (2008) 112(4):1493–502. doi: 10.1182/blood-2008-02-137398

574 43. Cluitmans JCA, Tomelleri C, Yapici Z, Dinkla S, Bovee-Geurts P, Chokkalingam V, et al.
575 Abnormal Red Cell Structure and Function in Neuroacanthocytosis. Connes P, editor. PLoS
576 One. (2015) 10(5):e0125580. doi: 10.1371/journal.pone.0125580

577 44. Samaras P, Schmidt T, Frejno M, Gessulat S, Reinecke M, Jarzab A, et al. ProteomicsDB: a
578 multi-omics and multi-organism resource for life science research. Nucleic Acids Res. (2019)
579 48(D1):D1153–63. doi: 10.1093/nar/gkz974

580 45. Rzepnikowska W, Flis K, Muñoz-Braceras S, Menezes R, Escalante R, Zoladek T. Yeast and
581 other lower eukaryotic organisms for studies of Vps13 proteins in health and disease. Traffic.
582 (2017) 18(11):711–9. doi: 10.1111/tra.12523

583 46. Zhang X, Kim T-H, Thauland TJ, Li H, Majedi FS, Ly C, et al. Unraveling the
584 mechanobiology of immune cells. Curr Opin Biotechnol. (2020) 66:236–45. doi:
585 10.1016/j.copbio.2020.09.004

586 47. Franco-Barraza J, Valdivia-Silva JE, Zamudio-Meza H, Castillo A, García-Zepeda EA,
587 Benítez-Bribiesca L, et al. Actin Cytoskeleton Participation in the Onset of IL-1β Induction of

588 an Invasive Mesenchymal-like Phenotype in Epithelial MCF-7 Cells. Arch Med Res. (2010)
589 41(3):170–81. doi: 10.1016/j.arcmed.2010.04.010

590 48. Lie PPY, Cheng CY, Mruk DD. The biology of interleukin-1: emerging concepts in the
591 regulation of the actin cytoskeleton and cell junction dynamics. Cell Mol Life Sci. (2012)
592 69(4):487–500. doi: 10.1007/s00018-011-0760-0

593 49. Lam WA, Rosenbluth MJ, Fletcher DA. Chemotherapy exposure increases leukemia cell
594 stiffness. Blood. (2007) 109(8):3505–8. doi: 10.1182/blood-2006-08-043570

595 50. Brown CD, Ghali HS, Zhao Z, Thomas LL, Friedman EA. Association of reduced red blood
596 cell deformability and diabetic nephropathy. Kidney Int. (2005) 67(1):295–300. doi:
597 10.1111/j.1523-1755.2005.00082.x

598 51. Kikuchi Y, Da Q-W, Fujino T. Variation in Red Blood Cell Deformability and Possible
599 Consequences for Oxygen Transport to Tissue. Microvasc Res. (1994) 47(2):222–31. doi:
600 10.1006/mvre.1994.1017

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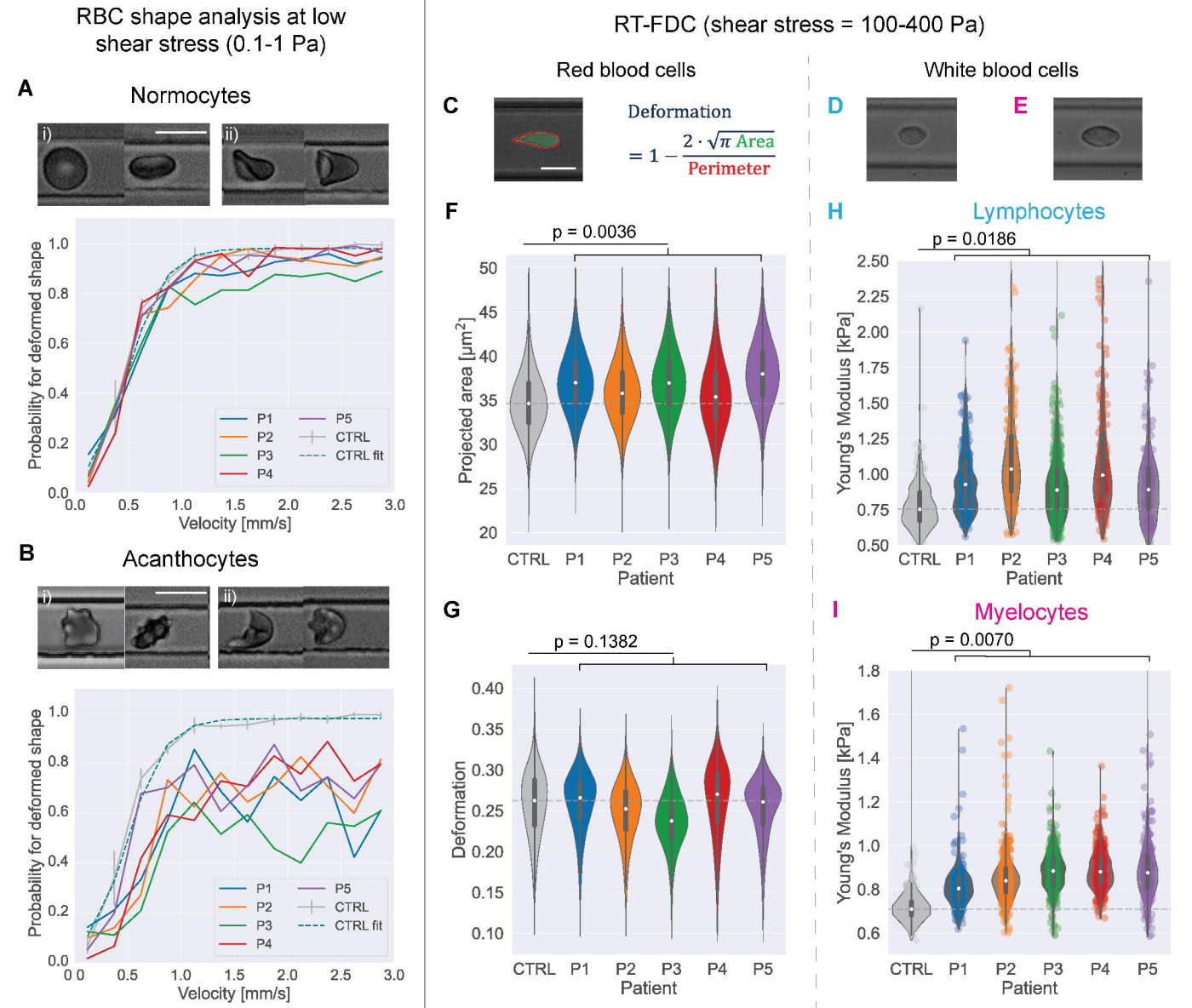
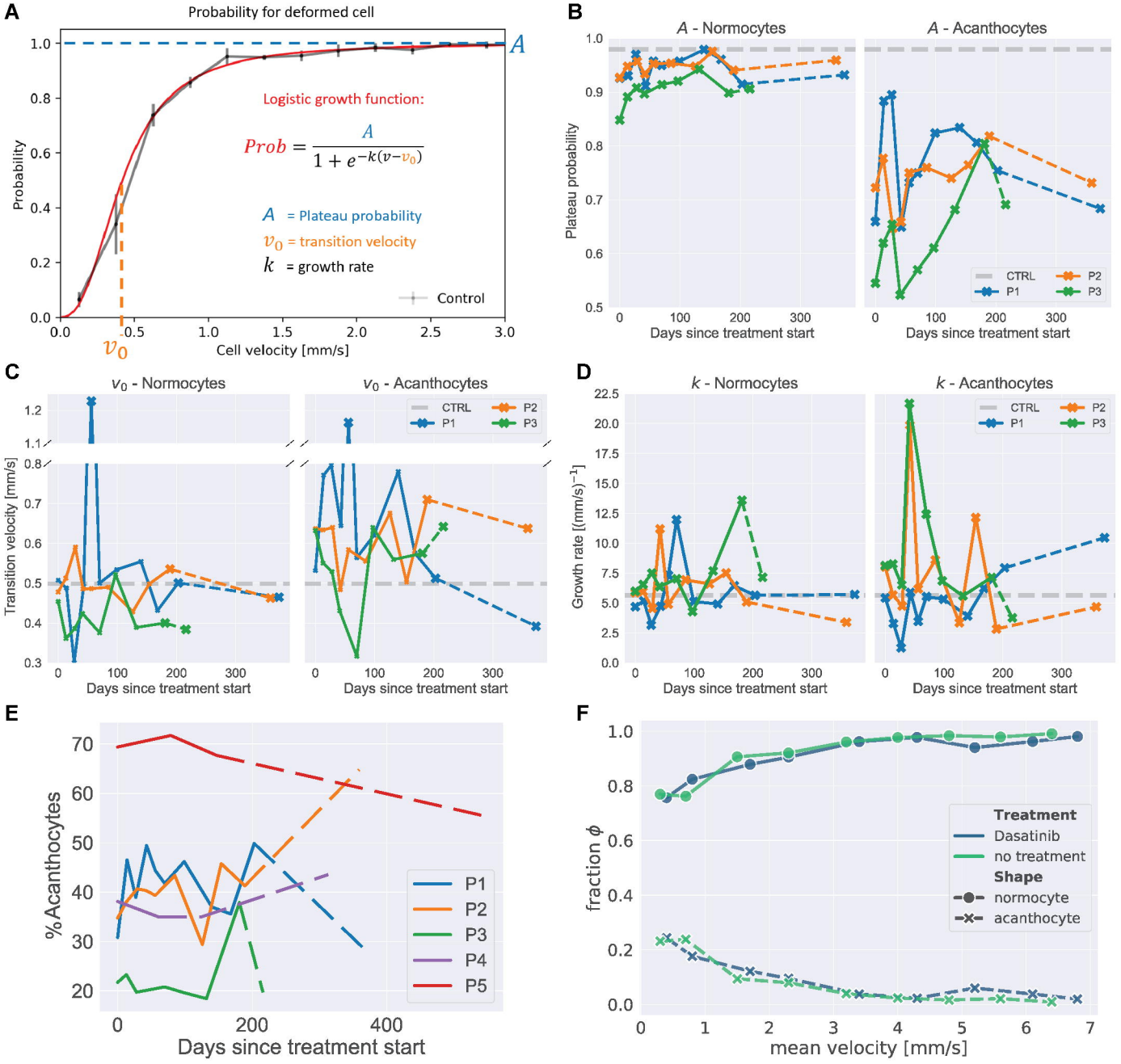
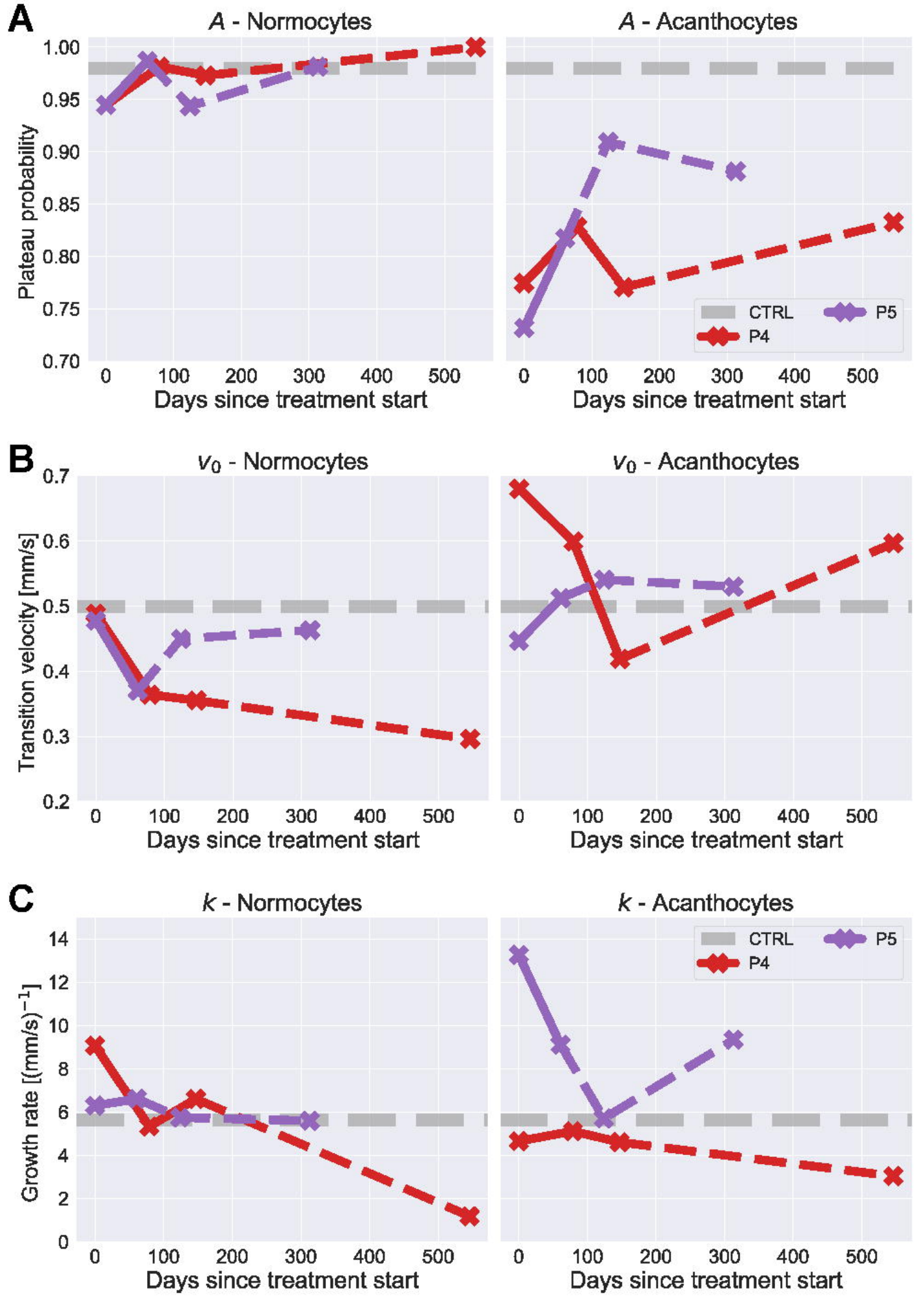
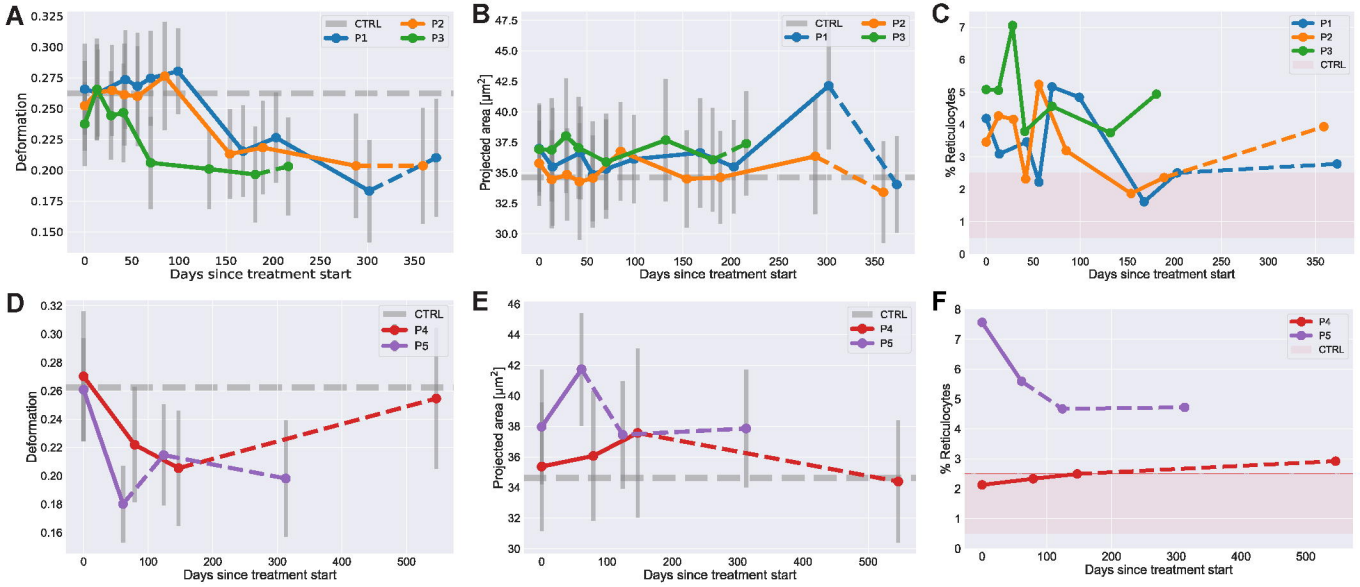
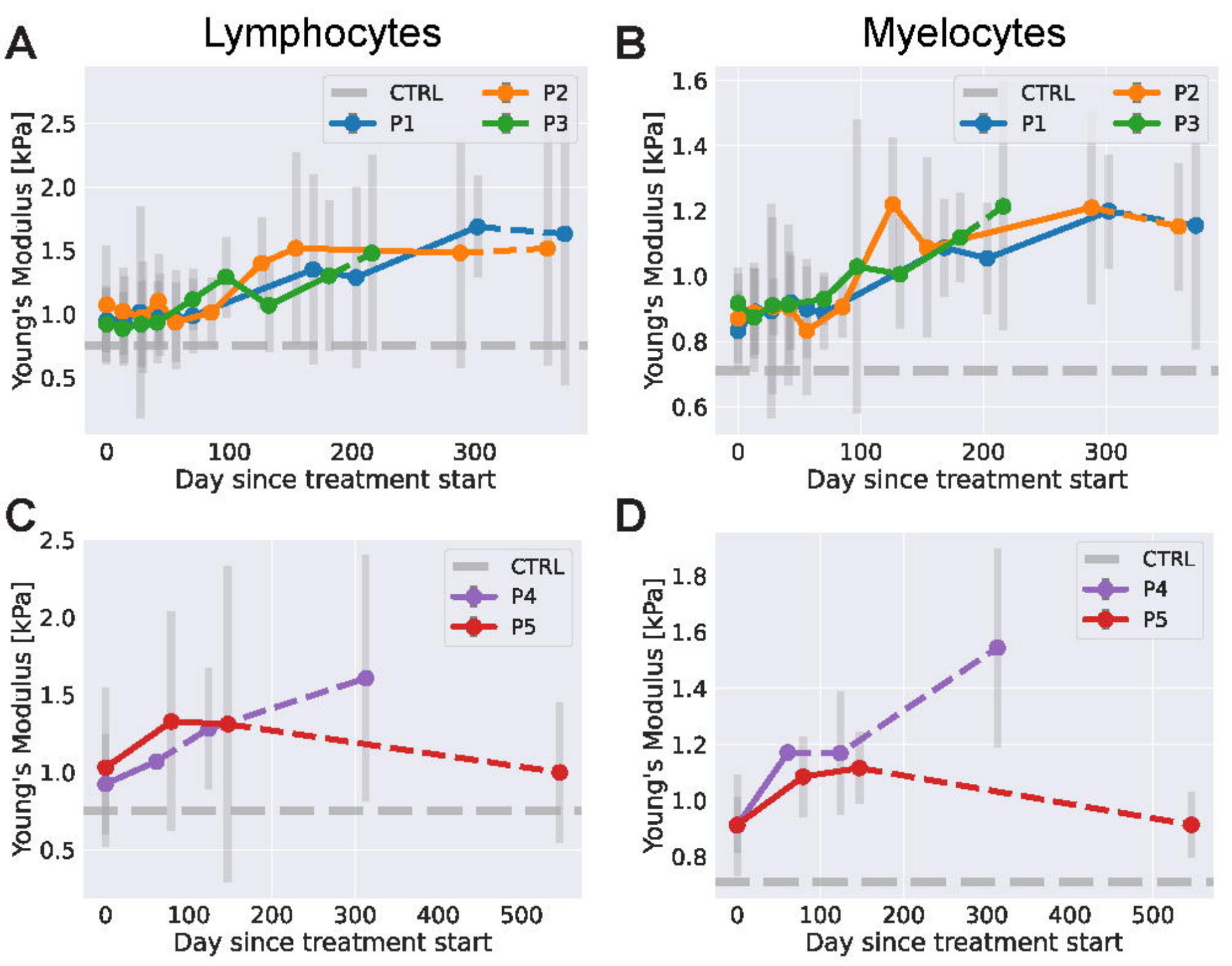

RBC shape analysis at low shear stress (0.1-1 Pa)
RT-FDC (shear stress = 100-400 Pa)
A
Normocytes
i)
ii)
Probability for deformed shape
Velocity [mm/s]
P1
P2
P3
P4
P5
CTRL
CTRL fit
B
Acanthocytes
Red blood cells
White blood cells
C
Deformation
$= 1 - \frac{2 \cdot \sqrt{\pi \text{ Area}}}{\text{Perimeter}}$
D
E
F
p = 0.0036
Projected area [µm²]
Patient
CTRL
P1
P2
P3
P4
P5
G
p = 0.1382
Deformation
H
Lymphocytes
p = 0.0186
Young's Modulus [kPa]
I
Myelocytes
p = 0.0070


A
Probability for deformed cell
Probability
Cell velocity [mm/s]
A
v_0
Logistic growth function:
$Prob = \frac{A}{1 + e^{-k(v - v_0)}}$
A = Plateau probability
v_0 = transition velocity
k = growth rate
Control
B
A - Normocytes
A - Acanthocytes
Plateau probability
Days since treatment start
CTRL
P1
P2
P3
C
v_0 - Normocytes
v_0 - Acanthocytes
Transition velocity [mm/s]
Days since treatment start
D
k - Normocytes
k - Acanthocytes
Growth rate [(mm/s)$^{-1}$]
Days since treatment start
E
%Acanthocytes
Days since treatment start
P1
P2
P3
P4
P5
F
fraction ϕ
mean velocity [mm/s]
Treatment
Dasatinib
no treatment
Shape
normocyte
acanthocyte


A
A - Normocytes
A - Acanthocytes
Plateau probability
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
100
200
300
400
500
Days since treatment start
CTRL
P5
P4
B
v_0 - Normocytes
v_0 - Acanthocytes
Transition velocity [mm/s]
0.7
0.6
0.5
0.4
0.3
0.2
C
k - Normocytes
k - Acanthocytes
Growth rate [(mm/s)$^{-1}$]
14
12
10
8
6
4
2
0


A
CTRL
P1
P2
P3
Deformation
Days since treatment start
B
CTRL
P1
P2
P3
Projected area [µm²]
Days since treatment start
C
P1
P2
P3
CTRL
% Reticulocytes
Days since treatment start
D
CTRL
P4
P5
Deformation
Days since treatment start
E
CTRL
P4
P5
Projected area [µm²]
Days since treatment start
F
P4
P5
CTRL
% Reticulocytes
Days since treatment start


A
Lymphocytes
B
Myelocytes
C
D
CTRL
P1
P2
P3
P4
P5
Young's Modulus [kPa]
Day since treatment start
0.5
0.6
0.8
1.0
1.2
1.4
1.5
1.6
1.8
2.0
2.5
0
100
200
300
400
500