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Comparison of Goldmann applanation and Ocular Response Analyser tonometry: intraocular pressure agreement and patient preference

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1 What was known before:

2 Mean difference between GAT and ORA IOPcc was reported to be 1.5 mmHg and
3 statistically significant in previous pooled analysis. Mean difference between GAT and ORA
4 IOPg was not reported in previous pooled analysis. There has been a paucity of research
5 into patient preferences for methods of tonometry.

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8 What this study adds:

9 There was no bias for ORA IOPcc compared to GAT but IOPg significantly underestimated
10 GAT by 0.83 mmHg. The relatively high percentage of differences between GAT and ORA
11 IOPcc and between GAT and ORA IOPg that were >2mmHg suggest that the methods are
12 not interchangeable. Participants showed no clear preference for either method of
13 tonometry.

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15 **Comparison of Goldmann applanation and Ocular Response Analyser**
16 **tonometry: intraocular pressure agreement, and patient preference**

17 This material is original research, has not been previously published and has
18 not been submitted for publication elsewhere while under consideration.

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34 **Title page**

35 **Comparison of Goldmann applanation and Ocular Response Analyser**

36 **tonometry: intraocular pressure agreement, and patient preference**

37 Running Title: Goldmann tonometry and Ocular Response Analyser

38 agreement

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54 Abstract

55 **Objectives:** To evaluate the agreement between Goldmann applanation
56 tonometry (GAT) and Ocular Response Analyser (ORA) intraocular pressure
57 (IOP) measurements, and patients' preferences.

58 **Methods:** Both eyes of participants in the Glaucoma within the Northern
59 Ireland Cohort for the Longitudinal Study of Ageing (GwNICOLA) were
60 included. Participants underwent GAT by a glaucoma expert and ORA
61 tonometry by investigators in a random order. Investigators were masked to
62 measurements between devices. Participants were asked which tonometer, if
63 any, they would prefer. We estimated the 95% limits of agreement (95% LoA)
64 and the variables that influence agreement between tonometers.

65 **Results:** There were 228 eyes of 120 participants included in this study.
66 Mean age of participants was 68.0 years (SD 8.79) and 52.5% were female.
67 For GAT – ORA IOPcc the mean difference with GAT (95%CI) was -0.23
68 mmHg (-0.57 mmHg, 0.11 mmHg) and the 95% LoA (95%CI) were 4.82
69 mmHg (5.15 mmHg, 4.48 mmHg) to -5.28 mmHg (-5.61 mmHg, -4.94
70 mmHg). 40.8% of eyes had an IOP difference of 2 mmHg or more between
71 GAT and ORA IOPcc. Corneal resistance factor (CRF) as estimated by ORA
72 influenced the agreement between GAT and ORA IOPcc. There were no
73 differences in preference for method of tonometry.

74 **Conclusions:** Although ORA IOPcc measurements with ORA did not show
75 significant bias compared to GAT the relatively large proportion of
76 measurement differences between ORA IOPcc and GAT that were > 2mmHg
77 indicates that GAT and ORA IOP measurements may not be

78 interchangeable. There were no differences in preference for method of
79 tonometry.

80 Introduction

81 Intraocular pressure (IOP) measurement is one of the main tests used to
82 make decisions in glaucoma despite IOP no longer forming part of the
83 disease definition. Since reduction of IOP is the only evidence-based therapy
84 for glaucoma, accurate measurement of IOP is important to assess response
85 to treatment and monitor the risk of progression. True IOP is rarely measured
86 directly because intracameral manometry is an invasive procedure.

87 Goldmann applanation tonometry (GAT) has been regarded as the reference
88 standard to measure IOP since the mid-1950s. Ready access to slit lamps,
89 low cost and ease of use for trained professionals may explain its appeal.

90 However, disadvantages of GAT include the expertise required to perform
91 the procedure, the subjective nature of determining the result and the
92 potential risk of infection due to tonometer contact with the cornea. In
93 contrast, non-contact tonometry has the advantages of having a lower risk of
94 infection, being automated and user friendly.

95 Many studies have focused on the influence of central corneal thickness
96 (CCT) on IOP measurement in normal and diseased eyes and it is now
97 widely accepted that IOP is overestimated in thick corneas and
98 underestimated in thin corneas, using all common types of tonometer.

99 Formulas and nomograms have been developed to correct for the effect of
100 CCT on IOP measured by GAT however the validity of these equations is
101 contested and their routine use is not recommended. (1,2)

102 Reichert's Ocular Response Analyser (ORA; Reichert, Inc., Depew, NY) is an
103 automated non-contact tonometer. ORA generates 2 measurements of IOP:

104 Goldmann correlated IOP (ORA IOPg) and corneal compensated IOP (ORA
105 IOPcc) and two measurements of corneal biomechanics: corneal hysteresis
106 (CH) and corneal resistance factor (CRF).

107 A systematic review of the agreement between GAT and ORA IOPcc by
108 Cook et al reported that the pooled mean difference from 12 included studies
109 was, 1.5 mmHg (95%CI 0.9 mmHg, 2.2 mmHg) and the pooled predicted
110 95% Limits of Agreement (95% LoA) were -3.9 mmHg to 7.0 mmHg. (2–14)
111 The mean differences reported from the included studies ranged from -0.07
112 mmHg (95%CI -0.51, 0.37) to 3.60 mmHg (95%CI 2.75, 4.45). The literature
113 review pointed to considerable heterogeneity in these measures and high risk
114 of bias across studies. It included papers through February 2010 but further
115 studies have since been conducted and the systematic review did not report
116 the agreement between GAT and ORA IOPg. Cook et al also highlighted the
117 paucity of studies investigating patient preferences for methods of IOP
118 measurement.

119 The primary aim of this study was to evaluate the agreement between GAT
120 and ORA measurements and to assess which covariates influence
121 agreement between these methods of tonometry. We also wished to
122 investigate participant preferences for IOP measurement using GAT and
123 ORA.

124 **Methods**

125 Guidelines for Reporting Reliability and Agreement Studies (GRRAS) were
126 followed in this study. (15) Both eyes of participants in the Glaucoma within
127 the Northern Ireland Cohort for the Longitudinal Study of Ageing

128 (GwNICOLA) were eligible for inclusion. GwNICOLA was a sub-study nested
129 within the Northern Ireland Cohort for the Longitudinal Study of Ageing
130 (NICOLA). The sample size was not specified a priori. NICOLA is an ongoing
131 longitudinal cohort study of ageing in a sample of the Northern Ireland
132 population aged 50 years or older. The “eligible population” for NICOLA was
133 defined as people aged 50 years or older (born on or before September 30th
134 1962) and living in private residential accommodation in Northern Ireland.
135 The sampling strategy identified addresses within postcode-based
136 geographic regions (geographic stratification). A fixed interval (systematic)
137 sample was drawn from each postcode-based geographical stratum.
138 NICOLA consisted of a Computerised Assisted Personal Interview (CAPI), a
139 self-completion questionnaire (SCQ) and a health assessment performed at
140 a later date. The health assessment included ophthalmic tests such as optic
141 disc stereophotography and IOP measurement with ORA tonometry. Data
142 collection for NICOLA began in February 2014 and ended in April 2018.

143 NICOLA participants of 50 years of age or older who attended the NICOLA
144 health assessment through 7th January 2017 and had a vertical cup to disc
145 ratio (VCDR) ≥ 0.7 and/or VCDR asymmetry ≥ 0.2 and/or vertical neuroretinal
146 rim ratio (NRRR) ≤ 0.1 on optic disc stereophotography and/or IOP ≥ 25
147 mmHg on ORA tonometry were eligible and invited for GwNICOLA. All
148 GwNICOLA examinations took place in the Northern Ireland Clinical
149 Research Facility in Belfast City Hospital between March and December
150 2017.

151 For NICOLA, ethical approval for the study was obtained from the School of
152 Medicine, Dentistry and Biomedical Sciences Ethics Committee, Queen’s

153 University Belfast. The GwNICOLA sub-study was approved by Northern
154 Ireland's Health and Social Care (HSC) Research Ethics Committee A (REC
155 A) (REC reference: 16/NI/0247). All participants of the NICOLA and
156 GwNICOLA studies gave written, informed consent. The NICOLA and
157 GwNICOLA studies were conducted according to "Good Clinical Practice"
158 guidance and the tenets of the Declaration of Helsinki.

159 At GwNICOLA, participants underwent Goldmann Applanation Tonometry
160 (GAT) by a glaucoma expert ophthalmologist (AAB) masked to ORA results
161 according to standard operating procedures. Sequential GAT readings were
162 not masked to the examiner (i.e., the tonometer dial was not covered). Two
163 diastolic GAT measurements were recorded and if there was a difference
164 greater than 2 mmHg between readings a third reading was taken. (16) The
165 GAT IOP was recorded as the mean GAT if two readings were taken and the
166 median GAT if three readings were taken. (16)

167 Subjects underwent ORA tonometry by a masked trained researcher (PMcC)
168 according to standard operating procedures. Three 'good quality'
169 measurements with a Waveform Score (WFS) >4 were captured and mean
170 results of IOP measurements and corneal biomechanical properties were
171 calculated. (17,18) Mean of three measurements was performed to attempt
172 to mitigate the added variability introduced by the ocular pulse amplitude
173 (OPA) by capturing the IOP during different phases of the cardiac cycle. (19)
174 Once three 'good quality' measurements were captured, no further
175 measurements were taken for that eye and no more than 5 consecutive
176 attempts were taken for each eye. The ORA measurement with the Best
177 Signal Values (BSV) was also recorded. BSV is the ORA measurement with

178 the highest WFS among the series of measurements per eye. Eyes with less
179 than three ORA measurements with a WFS >4 were excluded.

180 GAT and ORA were performed during the same session approximately 10
181 minutes apart. The order of GAT and ORA was randomly allocated using a
182 sealed envelope method. Non-contact anterior segment tomography
183 (Pentacam HR; Oculus, Wetzlar, Germany) was used to measure CCT and
184 anterior chamber volume (ACV) and non-contact optical biometry (LENSTAR
185 LS900; Haag-Streit, Koeniz, Switzerland) was used to measure axial length
186 (AL). GAT and ORA were calibrated according to manufacturer's instructions.

187 A questionnaire regarding the preferred method of intraocular pressure
188 measurement was given as soon as both procedures had been performed.
189 The preference study was performed on a convenience sample of
190 participants from GwNICOLA.

191 Statistical Analysis

192 Summary statistics of baseline continuous variables and frequencies of
193 categorical characteristics for GwNICOLA participants and for participants
194 included and excluded from the analysis are reported below. Comparisons
195 were made using independent sample t tests and χ^2 test for continuous
196 variables and categorical variables respectively. Summary statistics are
197 reported for included and excluded eyes and compared using generalised
198 estimating equations (GEE) to account for intra-individual correlations
199 between eyes. Ocular comorbidities including history of intraocular surgery
200 and trauma which may influence IOP measurement are also reported.

201 Inspection of histograms and Kolmogorov-Smirnov tests were used to check
202 for the normality of the distribution of differences in the measurements from
203 the two methods; GAT – ORA IOP_g and GAT – ORA IOP_{cc}. Mean bias and
204 95% LoA were estimated using GAT and ORA IOP measurements. A
205 sensitivity analysis was performed to measure mean bias and 95% LoA when
206 using ORA IOP BSV rather than mean of three measurements.

207 The percentage of eyes with an absolute difference greater than 2 mmHg
208 (which is considered to be a clinically significant difference) was calculated.

209 (2) Bland-Altman plot analysis was used to demonstrate proportional bias
210 where methods did not agree equally through the range of measurements.

211 Proportional bias was investigated using univariate linear regression of the
212 values of the difference between each method on the average of the two
213 methods.

214 GEE were then used to investigate how the two dependent variables; GAT –
215 ORA IOP_g and GAT – ORA IOP_c, varied according to selected independent
216 variables. The following parameters were considered as independent
217 variables in the univariate analysis using GEE: age, sex, glaucoma diagnosis
218 (per eye), ocular comorbidity, the order of GAT and ORA examination, CCT,
219 ACV, CH, CRF and AL.

220 Fisher's exact test was used to test for significant differences in the
221 proportions of participants who underwent GAT before ORA and ORA before
222 GAT who had preferences for GAT, ORA or no preference. Statistical
223 analysis was performed using a software program (IBM SPSS Statistics for
224 Windows, Version 24.0. Armonk, NY: IBM Corp).

225 Results

226 Baseline characteristics of participants of GwNICOLA and comparisons
227 between participants included and excluded from the agreement analysis are
228 presented in Table 1. Of both eyes from the 128 participants who attended
229 the GwNICOLA study, 228 eyes from 120 participants were included
230 following exclusion of eyes with less than three ORA measurements with
231 WFS > 4. Baseline characteristics of eyes included in the analysis and
232 differences between included and excluded are presented in Table 2.

233 The mean age of participants included in the analysis was 68.0 years and
234 52.5% of included participants were female. There was no significant
235 difference between the age of included and excluded participants. There
236 were 29 right eyes with ≥ 1 comorbidity and 32 left eyes with ≥ 1 comorbidity.
237 Comorbidities are described in Table 3.

238 Of the 120 participants included, 59 were randomised to undergo GAT before
239 ORA and 61 were randomised to undergo ORA before GAT. All ORA
240 readings were calculated from the mean of three measurements and all GAT
241 readings were calculated from the mean of 2 measurements.

242 The results of the agreement between measurements of IOP using GAT and
243 ORA are shown in Table 4. Bland Altman plots of the results are displayed in
244 Figure 1. ORA IOPg significantly underestimated GAT ($p < 0.001$) and the
245 mean difference between GAT and ORA IOPcc was not statistically
246 significant ($p = 0.20$). There was no statistically significant proportional bias
247 between mean IOP and GAT – ORA IOPg or between mean IOP and GAT –
248 ORA IOPcc. The percentage of eyes with an absolute difference greater than

249 2 mmHg between GAT and ORA IOPg and GAT and ORA IOPcc were
250 44.7% and 40.8% respectively. Sensitivity analysis showed that GAT – ORA
251 IOPg (BSV) mean bias was 0.95 (95%CI 0.62, 1.29; $p < 0.001$) and the 95%
252 LoA were 5.93 to -4.03, and that GAT – ORA IOPcc (BSV) mean bias was -
253 0.16 (95%CI -0.45, 0.23; $p = 0.53$) and the 95% LoA were 4.98 to -5.30.

254 Using GEE to combine the analysis of right and left eyes whilst accounting
255 for intra-individual correlation in univariate analysis, the following parameters
256 were statistically significantly associated with GAT – ORA IOPg: CRF (β -
257 0.363 $p < 0.001$) and CCT (β -0.020 $p < 0.001$). Using GEE, there were no
258 statistically significant correlations between GAT – ORA IOPg and age ($p =$
259 0.32), sex ($p = 0.27$), order of measurement ($p = 0.12$), diagnosis of
260 glaucoma ($p = 0.29$), ocular comorbidity ($p = 0.65$), AL ($p = 0.07$), CH ($p =$
261 0.16) or ACV ($p = 0.66$). There was significant multicollinearity between CCT
262 and CRF therefore they were not included in the same multivariate model.

263 Using GEE to combine the analysis of right and left eyes whilst accounting
264 for intra-individual correlation in univariate analysis, the following parameters
265 were statistically significantly associated with GAT – ORA IOPcc: CRF (β
266 0.484 $p < 0.001$) and CH (β 0.972 $p < 0.001$). Using GEE, there were no
267 statistically significant correlations between GAT – ORA IOPcc and age ($p =$
268 0.14), sex ($p = 0.61$), order of measurement ($p = 0.11$), diagnosis of
269 glaucoma ($p = 0.89$), ocular comorbidity ($p = 0.19$), CCT ($p = 0.09$), ACV ($p =$
270 0.74) or AL ($p = 0.07$). There was significant multicollinearity between CH
271 and CRF therefore they were not included in the same multivariate model.

272 There were 69 participants who completed the questionnaire which recorded
273 if the participant preferred GAT, ORA or had no preference. Most people (n =
274 40; 57.9%) reported no preference, but among those who expressed a
275 preference (n = 29) the majority chose ORA (n = 22). There were no
276 statistically significant associations between the order of ORA and GAT
277 measurement and participant preferences (Fisher's exact test $p = 0.19$).

278 **Discussion**

279 In the current study we investigated the agreement in IOP measurements
280 with GAT and ORA. We also investigated participant preference for IOP
281 measurement method.

282 The ORA IOP measurement is taken within milliseconds and has been
283 reported to be significantly correlated with OPA whereby IOP is variable
284 depending on which phase of the cardiac cycle the measurement is taken.
285 (14) Therefore it has been suggested that when the three ORA IOP
286 measurements are averaged, factors other than OPA must be important in
287 ORA IOP variability. (14) Our sensitivity analysis showed that the use of the
288 mean of three ORA measurements provided less mean bias and narrower
289 95% LoA between ORA IOP and GAT than the use of single ORA IOP BSV
290 measurements.

291 We report that ORA IOP_g systematically underestimated GAT by 0.83 mmHg
292 ($p < 0.001$) and ORA IOP_{cc} overestimated GAT by 0.23 mmHg ($p = 0.20$). We
293 demonstrated no bias for ORA IOP_{cc} compared to GAT which suggests that
294 ORA IOP_{cc} shows greater agreement with GAT than ORA IOP_g in this
295 population. There was no evidence of proportional bias between mean IOP

296 and GAT – ORA IOPcc or between mean IOP and GAT – ORA IOPg.
297 Although ORA IOPcc showed no significant mean difference compared to
298 GAT, the 95% LoA were wider for GAT – ORA IOPcc than for GAT – ORA
299 IOPg. However, the percentage of differences between ORA IOPcc and GAT
300 that were > 2mmHg was lower than the percentage of differences between
301 ORA IOPg and GAT that were > 2mmHg. This means that, although GAT –
302 ORA IOPcc has a wider 95% LoA, it has no significant mean bias and it has
303 fewer number of differences that were > 2mmHg, which may be the more
304 clinically relevant outcome because a difference > 2 mmHg would be
305 considered clinically significant. (2) It has been recommended that inter-
306 operator measurements for GAT should be within ± 4 mmHg of the mean
307 bias in 95% of eyes under ideal circumstances and in clinical practice these
308 figures may be considerably higher, however, analysis of inter-observer
309 variability was not performed for GAT or ORA in this study. (20) Our results
310 show that variability between GAT and ORA IOPg was ± 4.53 mmHg of the
311 mean bias in 95% of eyes and that variability between GAT and ORA IOPcc
312 was ± 5.05 mmHg of the mean bias in 95% of eyes. These findings suggest
313 that GAT and ORA IOP measurements may not be interchangeable however
314 the differences are relatively close to ± 4 mmHg of the mean bias in 95% of
315 eyes and the inclusion of comorbidities in this study population may be more
316 representative of clinical practice than ideal circumstances. Furthermore,
317 both GAT and ORA require corneal applanation to measure IOP, therefore,
318 without intracameral IOP measurement, we cannot determine whether GAT
319 or ORA IOP measurements are the superior measure of true IOP. It could be

320 that ORA is a superior measure even though GAT is the traditional gold
321 standard.

322 A diagnosis of glaucoma did not have a statistically significant effect on the
323 agreement between GAT and ORA measurements of IOP. The order of
324 measurement by the two measurement devices did not have a statistically
325 significant effect on the agreement between GAT and ORA IOPg and GAT
326 and ORA IOPcc. This suggests that there are no significant effects caused by
327 the application of drops and the tonographic applanation during GAT.

328 Our results differ from those of the systematic review by Cook et al (2) who
329 found a statistically significant mean difference of 1.5 mmHg between GAT
330 and ORA IOPcc. A number of studies that report the agreement between
331 GAT and ORA measurements of IOP were not included in the systematic
332 review by Cook et al. (21–28) The mean difference between GAT and ORA
333 IOPcc ranged between 0.8 mmHg and 8.3 mmHg and the mean difference
334 between GAT and ORA IOPg ranged between 0.86 mmHg and 7.2 mmHg in
335 these studies. (21,22) Direct comparisons between results of these studies
336 and our study is difficult due to differences in study populations and designs.

337 We showed that CRF and CCT were associated with the GAT – ORA IOPg
338 difference and that CRF and CH were statistically significantly associated
339 with the GAT – ORA IOPcc difference. Renier et al reported that the
340 difference between GAT and ORA IOPg was significantly associated with
341 CRF and the difference between GAT and ORA IOPcc was significantly
342 associated with CH. (28)

343 Cook et al reported that 46% of ORA IOPcc measurements were within 2
344 mmHg of GAT compared to our study in which we reported approximately
345 60% of ORA IOPcc measurements within 2mmHg of GAT. The lower
346 percentage of GAT – ORA IOPcc > 2mmHg in this study may be related to
347 the high level of expertise in the measurement of GAT. We also reported that
348 approximately 55% of ORA IOPg measurements within 2mmHg of GAT.

349 Our preference study indicated that participants tended to have no
350 preference or preferred ORA over GAT irrespective of the order of
351 measurement. This suggests that the application of anaesthetic drops did not
352 influence the preference for ORA over GAT. A study by Vandewalle et al
353 reported that no patients reported more than moderate discomfort with any of
354 the procedures in an agreement study which included GAT and ORA. (13)

355 This study had a number of strengths and limitations. Among the strengths
356 we would highlight the robust methods used to prevent risk of bias, including
357 randomisation of the order of testing, and masking of investigators. The study
358 included participants referred from a population-based study who were
359 suspected of having glaucoma. The results could possibly be similar to the
360 UK populations referred from the community to secondary care for definitive
361 diagnosis of glaucoma; however, generalisability is limited beyond this subset
362 of subjects.

363 Repeatability between ORA and GAT could not be meaningfully compared in
364 this study because sequential GAT readings were not masked (i.e., the
365 tonometer dial was not covered to the examiner) and it is therefore likely that
366 GAT repeatability would be highly biased. Unmasked GAT examination was

367 considered to be more representative of clinical practice. If ORA IOP were to
368 be more repeatable than GAT it may be of greater value, despite the
369 differences in measurements obtained with different devices.

370 Wang et al reported that, in healthy eyes, GAT had less variability than ORA
371 IOPg when GAT and ORA IOP were obtained by different observers but ORA
372 IOPg had less variability than GAT when GAT and ORA IOP were obtained
373 by the same observer. (19) Wang et al also found that ORA IOPcc was more
374 variable than ORA IOPg. ORA IOPcc is recognised to have greater variability
375 than ORA IOPg because ORA IOPcc is calculated using an algorithm
376 including ORA IOPg and corneal biomechanics, each with their own
377 variability. However, the study by Wang et al may not be generalizable to UK
378 populations referred from the community to secondary care due to its age
379 range, IOP range and the comorbidity profile. (19)

380 In conclusion, although systematic bias between GAT and ORA IOP readings
381 was of negligible clinical significance, the wide 95% LoAs and the high
382 percentage of differences greater than 2 mmHg suggest that GAT and ORA
383 IOP measurements may not be interchangeable in clinical practice. There
384 were no differences in patient preferences.

385 **References**

- 386 1. Guntav P, O'Leary DJ, Baskaran M, Broadway DC, Watkins RJ,
387 Vijaya L. Evaluation of tonometric correction factors. J Glaucoma.
388 2005;14(5):337–43.
- 389 2. Cook JA, Botello AP, Elders A, Fathi Ali A, Azuara-Blanco A, Fraser C,
390 et al. Systematic review of the agreement of tonometers with

- 391 Goldmann applanation tonometry. *Ophthalmology*. 2012;119(8):1552–
392 7.
- 393 3. Kirwan C, O’Keefe M. Measurement of intraocular pressure in LASIK
394 and LASEK patients using the Reichert Ocular Response Analyzer and
395 Goldmann applanation tonometry. Vol. 24, *Journal of refractive
396 surgery*. 2008. p. 366–70.
- 397 4. Ehongo A, De Maertelaer V, Pourjavan S. Effect of topical corneal
398 anaesthesia on ocular response analyzer parameters: Pilot study. *Int
399 Ophthalmol*. 2009;29(5):325–8.
- 400 5. Kotecha A, White E, Schlottmann PG, Garway-Heath DF. Intraocular
401 Pressure Measurement Precision with the Goldmann Applanation,
402 Dynamic Contour, and Ocular Response Analyzer Tonometers.
403 *Ophthalmology*. 2010;117(4):730–7.
- 404 6. Oncel B, Dinc UA, Orge F, Yalvaç BI. Comparison of IOP
405 measurement by ocular response analyzer, dynamic contour,
406 Goldmann applanation, and noncontact tonometry. *Eur J Ophthalmol*.
407 2009;19(6):936–41.
- 408 7. Kynigopoulos M, Schlote T, Kotecha A, Tzamalīs A, Pajic B, Haefliger
409 I. Repeatability of intraocular pressure and corneal biomechanical
410 properties measurements by the ocular response analyser. *Klin Monbl
411 Augenheilkd*. 2008;225(5):357–60.
- 412 8. Lam A, Chen D, Chiu R, Chui WS. Comparison of IOP measurements
413 between ORA and GAT in normal Chinese. *Optom Vis Sci*.

- 414 2007;84(9):909–14.
- 415 9. Pepose JS, Feigenbaum SK, Qazi MA, Sanderson JP, Roberts CJ.
416 Changes in Corneal Biomechanics and Intraocular Pressure Following
417 LASIK Using Static, Dynamic, and Noncontact Tonometry. *Am J*
418 *Ophthalmol.* 2007;143(1):39–47.
- 419 10. Kotecha A, Elsheikh A, Roberts CR, Zhu H, Garway-Heath DF.
420 Corneal thickness- and age-related biomechanical properties of the
421 cornea measured with the ocular response analyzer. *Investig*
422 *Ophthalmol Vis Sci.* 2006;47(12):5337–47.
- 423 11. Medeiros FA, Weinreb RN. Evaluation of the influence of corneal
424 biomechanical properties on intraocular pressure measurements using
425 the ocular response analyzer. *J Glaucoma.* 2006;15(5):364–70.
- 426 12. Morita T, Shoji N, Kamiya K, Hagishima M, Fujimura F, Shimizu K.
427 Intraocular pressure measured by dynamic contour tonometer and
428 ocular response analyzer in normal tension glaucoma. *Graefe's Arch*
429 *Clin Exp Ophthalmol.* 2010;248(1):73–7.
- 430 13. Vandewalle E, Vandenbroeck S, Stalmans I, Zeyen T. Comparison of
431 ICare, dynamic contour tonometer, and ocular response analyzer with
432 Goldmann applanation tonometer in patients with glaucoma. *Eur J*
433 *Ophthalmol.* 2009;19(5):783–9.
- 434 14. Sullivan-Mee M, Gerhardt G, Halverson KD, Qualls C. Repeatability
435 and reproducibility for intraocular pressure measurement by dynamic
436 contour, ocular response analyzer, and goldmann applanation

- 437 tonometry. *J Glaucoma*. 2009;18(9):666–73.
- 438 15. Kottner, J, Audigé L, Brorson S, Donner A, Gajewski BJ HA. Guidelines
439 for Reporting Reliability and Agreement Studies (GRRAS) were
440 proposed. *J Clin Epidemiol*. 2011;64:96–106.
- 441 16. Kass M. Standardizing the measurement of intraocular pressure for
442 clinical research. *Ophthalmology*. 1996;103(1):183–5.
- 443 17. Vantomme M, Pourjavan S, Detry-Morel M. The range of the waveform
444 score of the ocular response analyzer (ora) in healthy subjects. *Bull
445 Soc Belge Ophtalmol*. 2013;322:91–7.
- 446 18. Lam AKC, Chen D, Tse J. The Usefulness of Waveform Score from the
447 Ocular Response Analyzer. *Optom Vis Sci*. 2010;87(3).
- 448 19. Wang AS, Alencar LM, Weinreb RN, Tafreshi A, Deokule S, Vizzeri G,
449 et al. Repeatability and Reproducibility of Goldmann Applanation,
450 Dynamic Contour, and Ocular Response Analyzer Tonometry. *J
451 Glaucoma*. 2013;22:127–32.
- 452 20. Garway-Heath DF, Kotecha A, Lerner F, Dayanir V, Brandt J, Pepose
453 J, et al. Measurement of Intraocular Pressure. In: Weinreb RN, Brandt
454 JD, Garway-Heath D, Medeiros F, editors. *Intraocular Pressure World
455 Glaucoma Association Consensus Series 4*. Kugler; 2007. p. 17–54.
- 456 21. Martinez-De-La-Casa JM, Garcia-Feijoo J, Fernandez-Vidal A,
457 Mendez-Hernandez C, Garcia-Sanchez J. Ocular response analyzer
458 versus Goldmann applanation tonometry for intraocular pressure
459 measurements. *Investig Ophthalmol Vis Sci*. 2006;47(10):4410–4.

- 460 22. Kouchaki B, Hashemi H, Yekta A, khabazkhoob M. Comparison of
461 current tonometry techniques in measurement of intraocular pressure.
462 J Curr Ophthalmol. 2017;29(2):92–7.
- 463 23. Carbonaro F, Andrew T, MacKey DA, Spector TD, Hammond CJ.
464 Comparison of three methods of intraocular pressure measurement
465 and their relation to central corneal thickness. Eye. 2010;24(7):1165–
466 70.
- 467 24. Bayoumi NHL, Bessa AS, El Massry AAK. Ocular response analyzer
468 and Goldmann applanation tonometry: A comparative study of findings.
469 J Glaucoma. 2010;19(9):627–31.
- 470 25. Lau W, Pye D. A clinical description of ocular response analyzer
471 measurements. Investig Ophthalmol Vis Sci. 2011;52(6):2911–6.
- 472 26. Ehrlich JR, Haseltine S, Shimmyo M, Radcliffe NM. Evaluation of
473 agreement between intraocular pressure measurements using
474 Goldmann applanation tonometry and Goldmann correlated intraocular
475 pressure by Reichert's ocular response analyser. Eye.
476 2010;24(10):1555–60.
- 477 27. Ehrlich JR, Radcliffe NM, Shmmyo M. Goldmann Applanation
478 Tonometry compared with corneal-compensated intraocular pressure
479 in the evaluation of primary open-angle Glaucoma. BMC Ophthalmol.
480 2012;12(1):52.
- 481 28. Renier C, Zeyen T, Fieuws S, Vandenbroeck S, Stalmans I.
482 Comparison of ocular response analyzer, dynamic contour tonometer

483 and Goldmann applanation tonometer. *Int Ophthalmol.*
484 2010;30(6):651–9.

485 Titles and legends to figures

486 Figure 1. Bland Altman plot between GAT and ORA IOPg (left) and GAT and
487 ORA IOPcc (right)

488

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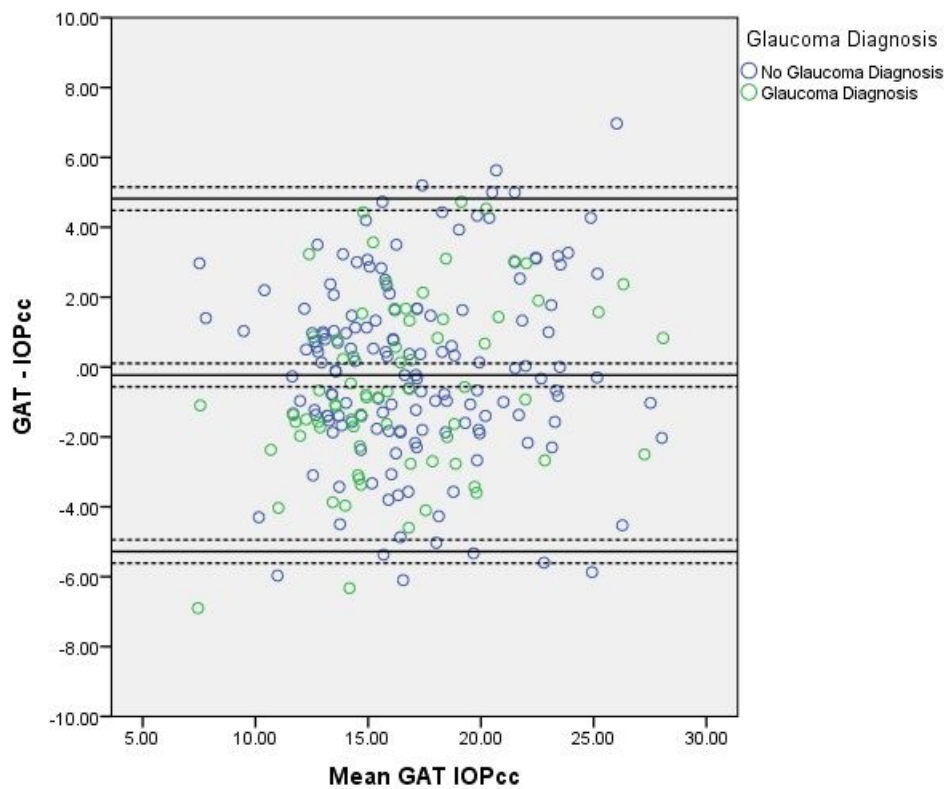
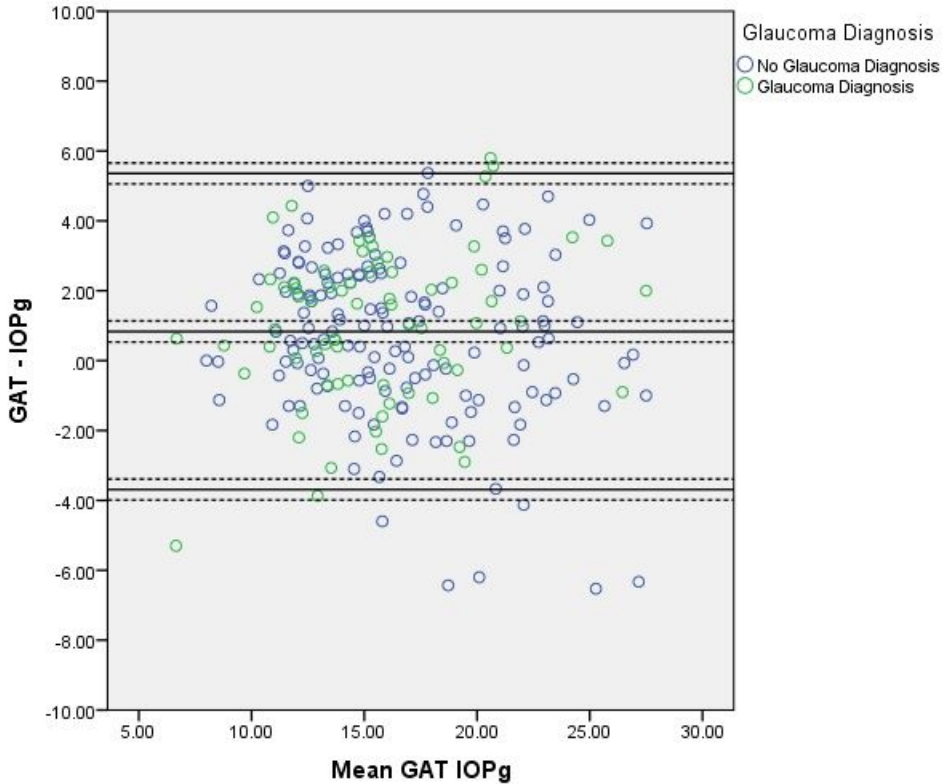


Table 1. Baseline characteristics of participants of GwNICOLA and comparison between participants included and excluded from the agreement analysis

	GwNICOLA Cohort (n = 128)	Participants included in agreement analysis (n = 120)	Participants excluded in agreement analysis (n = 8)	P value
Mean Age \pm SD	68.31 \pm 8.78	68.00 \pm 8.79	73.00 \pm 7.64	0.12
Sex (% female)	53.1	52.50	62.50	0.72

Table 2. Comparison of characteristics of included and excluded eyes

	Included eyes (n = 228)	Excluded eyes (n = 28)	P value †
Eyes (% right)	50.00	50.00	1.000 ^a
Glaucoma diagnosis (%)	32.90	39.30	0.50 ^a
GAT ± SD (mmHg)	16.75 ± 4.46 (n = 228)	19.07 ± 5.22 (n = 28)	0.16
ORA IOPg ± SD (mmHg)	15.92 ± 4.61 (n = 228)	16.60 ± 6.22 (n = 16)	0.88
ORA IOPcc ± SD (mmHg)	16.97 ± 4.07 (n = 228)	17.93 ± 6.48 (n = 16)	0.90
CRF ± SD (mmHg)	10.05 ± 2.03 (n = 228)	9.95 ± 1.91 (n = 16)	0.70
CH ± SD (mmHg)	9.82 ± 1.53 (n = 228)	9.47 ± 1.93 (n = 16)	0.90
WFS ± SD	6.94 ± 0.97 (n = 228)	5.80 ± 1.38 (n = 16)	<0.001
CCT ± SD (µm)	544.32 ± 36.15 (n = 216)	541.57 ± 44.86 (n = 21)	0.17
ACV ± SD	144.69 ± 38.50 (n = 216)	154.38 ± 39.57 (n = 21)	0.048
AL ± SD (mm)	23.98 ± 1.29 (n = 220)	23.33 ± 1.40 (n = 26)	0.45

† Generalised estimating equation unless otherwise stated, a – χ^2 test

Table 4. Agreement analysis: Intraocular pressure (IOP) results from Ocular Response Analyser (ORA) and Goldmann applanation tonometry (GAT)

	ORA IOPg	ORA IOPcc
Mean difference with GAT (95%CI)	0.83 (0.53, 1.13)	-0.23 (-0.57, 0.11)
95% LoA with GAT (95%CI)	5.36 (5.66, 5.06) to -3.69 (-3.99, -3.39)	4.82 (5.15, 4.48) to -5.28 (-5.61, -4.94)
Absolute difference between GAT and ORA >2 mmHg (%)	44.70	40.80

Table 3. Ocular comorbidities in included right and left eyes

Comorbidity	Right eyes	Left eyes
History of cataract surgery	15	16
History of refractive surgery	3	6
History of retinal surgery	2	1
History of trauma	0	1