Package ‘BDP2’

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Description Tools and workflow to choose design parameters in Bayesian adaptive single-arm phase II trial designs with binary endpoint (response, success) with possible stopping for efficacy and futility at interim analyses. Also contains routines to determine and visualize operating characteristics. See Kopp-Schneider et al. (2018) <doi:10.1002/bimj.201700209>.
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Description

Tools and workflow to choose design parameters in Bayesian adaptive single-arm phase II trial designs with binary endpoint (response, success) with possible stopping for efficacy and futility at interim analyses. Also contains routines to determine and visualize operating characteristics. See Kopp-Schneider et al. (2018) <doi:10.1002/bimj.201700209>.

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Operating characteristics of a single-arm trial with a binary endpoint with stopping for futility and stopping for efficacy. plotNce_vs_pecall plot objects returned by plotBDP2() plotBDP2 Plots

Tools and workflow to choose design parameters in Bayesian adaptive single-arm phase II trial designs with binary endpoint (response, success) with possible stopping for efficacy and futility at interim analyses. Also contains routines to determine and visualize operating characteristics. Main functions: BDP2workflow, BDP2 and plotBDP2. BDP2workflow provides an interactive shiny app which also generates Word/pdf/html reports.

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References

Examples
```r
## Not run:
# Starts Shiny app
BDP2workflow()
## End(Not run)
```

Description
Determines the operating characteristics of a single-arm trial with a binary endpoint (response, success) and interim efficacy and futility analyses. Declaration of efficacy and futility (including possibly early stopping) is based on the posterior probability that the true response rate is at least pE, pF respectively.

Usage
```r
BDP2(n, interim.at, ptrue, eff.stop = FALSE, pF, cf, pE = NULL, cE = NULL, type="PostProb", alpha=0.05, shape1F, shape2F, shape1E = NULL, shape2E = NULL, simulate = FALSE, nsim = 10000)
```
Arguments

n sample size at the final analysis
interim.at vector of sample sizes at the interim analyses
ptrue true (assumed) response rate used for analytical evaluations or simulating the trial
eff.stop FALSE: No evaluation of efficacy. "call": no stop for efficacy: in this case the program merely calculates the probability that the efficacy criterion is satisfied (possibly triggering a notification of the DMC and the start of the planning of a subsequent trial). "stop": the study ends if the efficacy criterion is reached at an interim analysis.
pF response rate used for the futility criterion (may be identical to pE)
cF critical level of posterior probabilities used for declaring futility
pE response rate used for the efficacy criterion
cE critical level of posterior probabilities used for declaring efficacy
type "PostProb" for decisions based on posterior probabilities (default) or "PredictivePower" for decisions based on predictive power (currently only implemented for simulate==TRUE)
alpha significance level for final test (only for simulate==TRUE & type=="PredictivePower")
shape1F first parameter of the Beta prior for futility analysis
shape2F second parameter of the Beta prior for futility analysis
shape1E first parameter of the Beta prior for efficacy analysis
shape2E second parameter of the Beta prior for efficacy analysis
simulate FALSE for analytical evaluation and TRUE for simulation
nsim number of simulation runs (only used if simulate==TRUE)

Details

Assumptions: Endpoint (response/no response) data available for all study patients. Beta-binomial model. Prior distribution = Beta(shape1, shape2).

Decisions based on posterior probabilities:
The posterior distribution at interim analysis with n.int patients and k.int successes is Beta(k.int + shape1F, n.int + shape2F - k.int) and Beta(k.int + shape1E, n.int + shape2E - k.int), respectively. Efficacy is declared if the posterior probability P(true response rate > pE) is >= cE. Futility is declared if the posterior probability P(true success rate > pF) is < cF. cF, cE translate into futility/efficacy boundaries (maximum number of responses leading to early termination for futility/minimum number of responses leading to declaring of, or early termination for, efficacy).

Decisions based on predictive power: Given the results of the interim analysis, the predictive power at the final analysis (n patients, critical number of successes k.crit) is P(X >= k.crit - k.int), where X follows a beta-binomial distribution with parameters n'= n - n.int, a = k.int + shape1, and b = n.int - k.int + shape2.

Efficacy is declared if the predictive power is >= cE (cE must be high, e.g. 0.70). Futility is declared if the predictive power is < cF (cF must be small, e.g. 0.10). cE, cF translate into futility/efficacy boundaries (maximum number of responses leading to early termination for futility/minimum number of responses leading to declaring of, or early termination for, efficacy).
References


Examples

```r
# Operating characteristics with calling for efficacy
BDP2(n=20, interim.at = c(3,9,13,18), ptrue = 0.3, 
    eff.stop = "call", 
    pF=0.3, cF=0.01, pE=0.12, cE = 0.9, 
    type="PostProb", 
    shape1F=0.3, shape2F=0.7, shape1E=0.12, shape2E=0.88)

# Operating characteristics with stopping for efficacy
BDP2(n=20, interim.at = c(3,9,13,18), ptrue = 0.3, 
    eff.stop = "stop", 
    pF=0.3, cF=0.01, pE=0.12, cE = 0.9, 
    type="PostProb", 
    shape1F=0.3, shape2F=0.7, shape1E=0.12, shape2E=0.88)
```

**Description**

Starts a shiny app in the web browser. It provides a workflow to choose design parameters single-arm trial with a binary endpoint (response, success) and interim efficacy and futility analyses as well as routines to determine and visualize operating characteristics. Also Word/pdf/html reports can be generated.

**Usage**

```r
BDP2workflow(display.mode = "normal")
```

**Arguments**

- `display.mode` display.mode passed to `shiny::runApp()`

**References**

Examples

```r
## Not run:
# Starts Shiny app
BDP2workflow()
## End(Not run)
```

### BDP2_simulate

Simulated operating characteristics of a single-arm trial with a binary endpoint for different types of futility criteria

#### Description

**NOTE:** Usually function `BDP2` will be preferred.

Determines the operating characteristics of a single-arm trial with a binary endpoint (success - failure) and interim futility analyses. The user can choose among 10 futility criteria, which are based on predictive or conditional power (the latter either assuming H1 or the MLE), posterior or predictive probabilities, tail probabilities (under H0 or H1), constant success rates, or arbitrary user-defined futility bounds.

Assumptions: Endpoint (success/no success) data available for all study patients. In case of Bayesian analysis: Beta-binomial model. Prior distribution = Beta(shape1,shape2) (uniform if prior.mean=0.5,prior.sampleSize=2).

In case of predictive or conditional power, tail probabilities, or rates: One-sided testing in the final analysis.

#### Usage

```r
BDP2_simulate(n, vn.int, p, p0, p1, alpha = 0.05, crit, type = 5, nsim, shape1 = 1, shape2 = 1)
```

#### Arguments

- **n**: sample size at the final analysis
- **vn.int**: vector of sample sizes at the interim analyses (the vector may be equal to 1:(n-1) = continuous monitoring of futility)
- **p**: true (assumed) success rate used for simulating the trial
- **p0**: success rate corresponding to H0
- **p1**: success rate corresponding to H1 (p1 > p0)
- **alpha**: nominal probability of type 1 error used for the final test
- **crit**: critical level(s) of predictive/conditional power, (posterior) probabilities, rates, or patient numbers used for early termination. crit translates into futility boundaries (maximum number of successes leading to early termination). If simple rates are used for monitoring futility (type=7), crit is the critical success rate. Rates or probabilities must be input as percentages (???). In case of type 10 analyses, crit must be a vector of numbers of successes indicating futility bounds at each (interim or final) analysis.
**Details**

Some methodological details on the 10 types of futility criteria:

**Type 1:** Predictive power. Given the results of the interim analysis the predictive power at the final analysis (n patients, critical number of successes k.crit) is \( P(X \geq k.crit - k.int) \), where \( X \) follows a beta-binomial distribution with parameters \( n' = n - n.int, a = k.int + shape1, \) and \( b = n.int - k.int + shape2 \).

**Type 2,3:** Conditional power. The conditional power at the interim analysis is \( P(X \geq k.crit - k.int) \), where \( X \) follows a binomial distribution with parameters \( n' = n - n.int, \) and success probability either equal to \( p1 \) (futility analysis type 2) or to the estimated success rate (MLE) at the interim analysis (type 3).

**Type 4,5:** Posterior probabilities. The posterior distribution at interim analysis with \( n.int \) patients and \( k.int \) successes is \( Beta(k.int + shape1, n + shape2 - k.int) \). Type 4: Futility is declared if the posterior probability \( P(true\ success\ rate > p0) \) is < crit. (Here, crit must be large, e.g. 70%). Type 5: Futility is declared if the posterior probability \( P(true\ success\ rate \geq p1) \) is < crit. (Here, crit must be small, e.g. 10%).

**Type 6:** Predictive probability combined with posterior probability. Futility is declared if the posterior predictive probability that the study will be a success is < crit (e.g. 10%). Here, the success is defined by the total number of successes in the trial yielding a posterior probability of at least 1 - alpha (when evaluated in the final analysis) that the true success rate is > p0.

**Type 7:** Estimated success rates. Futility is declared if the success rate is smaller than a fixed benchmark crit. The final analysis is test-based.

**Type 8,9:** Tail probabilities under H0,H1. Type 8: The futility criterion uses an alpha level crit that is constant across all interim analysis. The final analysis is test-based. Futility is declared if the p-value (upper tail) is \( \leq \) crit. Type 8 futility analyses should only be used if the number of patients at the first interim analysis is not too low (say, at least 5 to 10). The value of crit is not identical to the alpha level used in the final test. Generally, a fairly high value of crit will be appropriate (e.g. 70%). Type 9: Similar to type 8, but with lower-tail probabilities calculated under H1 (“p-values under H1”). I.e., futility is declared if, under H1, the probability of obtaining at most as many successes as the observed number is < crit (“observed number of successes “too low” to be compatible with H1 at one-sided significance level = crit). Generally, a small value of crit (e.g. 5% or 10%) should be chosen.

**Type 10:** User-defined boundaries. Here, the futility boundaries (maximum numbers of successes leading to early termination) are directly input by the user. crit ist the vector of these boundaries at
each (interim or final) analysis. The study is terminated if the number of successes is at analysis no. m is <= the crit[m].

Examples

BDP2_simulate(n=30, vn.int=c(10,20),
              p=0.2, p0=0.1, p1=0.3, crit=0.1, type=5, nsim=1000, shape1=1, shape2=1)

crit_general

Calculates CritBoundaries for different types of futility criteria

Description

Calculates CritBoundaries for different types of futility criteria

Usage

crit_general(n, p0, p1, vn.int, alpha, crit, type=5, shape1 = 1, shape2 = 1)

Arguments

n sample size at the final analysis
p0 success rate corresponding to H0
p1 success rate corresponding to H1 (p1 > p0)
vn.int vector of sample sizes at the interim analyses (the vector may be equal to 1:(n-1) = continuous monitoring of futility)
alpha nominal probability of type 1 error used for the final test
crit critical level(s) of predictive/conditional power, (posterior) probabilities, rates, or patient numbers used for early termination. crit translates into futility boundaries (maximum number of successes leading to early termination). If simple rates are used for monitoring futility (type=7), crit is the critical success rate. Rates or probabilities must be input as percentages. In case of type 10 analyses, crit must be a vector of numbers of successes indicating futility bounds at each (interim or final) analysis.
type see BDP2_simulate for details. Type of futility analysis: 1=predictive power;
2=conditional power under H1; 3=conditional power under the MLE; 4=poster-
ior probability of a success rate > p0; 5=posterior probability of a success rate 
>= p1; 6=predictive probability of reaching a "positive" final study result, where 
"positive" is defined in terms of the posterior probability of a success rate > p0. 
(Here, the critical level must be >= 1 - alpha). 7=estimated success rate; 8=p-
values; 9="p-values under H1"; 10=user- defined bounds (a vector of critical 
numbers of successes for each analysis)
shape1 for prior distribution
shape2 for prior distribution
pfstop

Operating characteristics of a single-arm trial with a binary endpoint with futility stopping

Description

Determines the operating characteristics of a single-arm trial with a binary endpoint (success - failure) on the basis of analytical derivations. The design allows for futility stopping. Outputs are

- probability of futility stopping (P.futil) at each interim analysis
- cumulative stopping probability up to the interim (P.futil.cum).

Usage

pfstop(p, vn.int, v.crit)

Arguments

p true response rate
vn.int vector of sample sizes at the interim analyses
v.crit vector of critical boundaries for futility stopping at the interim analyses (stop for futility if number of successes <= boundary). Choose boundary=-1 if no stopping is allowed.

Examples

pfstop(p=0.3, vn.int=c(3,9,13,18,20), v.crit=c(0,1,2,3,3))

pfstopEcall

Operating characteristics of a single-arm trial with a binary endpoint with futility stopping and calling efficacy at interim

Description

Determines the operating characteristics of a single-arm trial with a binary endpoint (success - failure) on the basis of analytical derivations. The design allows for futility stopping and evaluates efficacy at interim. Outputs are

- probability of calling efficacy (P.effic) at each interim analysis
- cumulative probability of calling efficacy up to the interim (P.effic.cum).
- probability of futility stopping (P.futil) at each interim analysis
- cumulative stopping probability up to the interim (P.futil.cum).
Usage

pFstopEcall(p, vn.int, v.critE, v.critF)

Arguments

- **p**: true response rate
- **vn.int**: vector of sample sizes at the interim analyses
- **v.critE**: vector of critical boundaries for calling efficacy at the interim analyses (call efficacy if number of successes >= boundary)
- **v.critF**: vector of critical boundaries for futility stopping at the interim analyses (stop for futility if number of successes <= boundary). Choose boundary=-1 if no stopping for futility is allowed.

Examples

pFstopEcall(p=0.3, vn.int=c(3,9,13,18,20), v.critE=4:8, v.critF=c(0,1,2,3,3))

---

**pFstopEstop**

*Operating characteristics of a single-arm trial with a binary endpoint with stopping for futility and stopping for efficacy*

Description

Determines the operating characteristics of a single-arm trial with a binary endpoint (success - failure) on the basis of analytical derivations. The design allows for stopping for futility and stopping for efficacy. Outputs are

- probability of stopping for efficacy (P.effic) at each interim analysis
- cumulative probability of stopping for efficacy up to the interim (P.effic.cum).
- probability of futility stopping (P.futil) at each interim analysis
- cumulative stopping probability up to the interim (P.futil.cum).

Usage

pFstopEstop(p, vn.int, v.critE, v.critF)

Arguments

- **p**: true response rate
- **vn.int**: vector of sample sizes at the interim analyses
- **v.critE**: vector of critical boundaries for calling efficacy at the interim analyses (stop for efficacy if number of successes >= boundary)
- **v.critF**: vector of critical boundaries for futility stopping at the interim analyses (stop for futility if number of successes <= boundary). Choose boundary=-1 if no stopping for futility is allowed.
Examples

```r
pFstopEstop(p=0.3, vn.int=c(3, 9, 13, 18, 20), v.critE=4:8, v.critF=c(0, 1, 2, 3, 3))
```

---

**plot.cE_vs_pEcall**  
*Plot objects returned by plotBDP2()*

Description

Plot objects returned by `plotBDP2` with arguments `x = "cE"` and either `y = "PEcall"` or `y = "PEstop"` which can computationally be relatively expensive.

Usage

```r
## S3 method for class 'cE_vs_pEcall'
plot(x, ...)
## S3 method for class 'cE_vs_pEstop'
plot(x, ...)
```

Arguments

- `x`  
  Object returned by `plotBDP2` with arguments `x = "cE"` and either `y = "PEcall"` or `y = "PEstop"

- `...`  
  arguments passed to `plot.default`

Examples

```r
shape1f=PNS
shapeRf=PN7
shape1e=PN1R
shapeRe=PN88
res=plotBDP2(x="cE", y="PEcall", n=30, interim.at=15, 
  pF=0.3, CF=0.01, pE=0.12, CE=seq(0.5, 1, by=.01), p0=0.3, p1=0.12, 
  shape1F=shape1F, shape2F=shape2F, shape1E=shape1E, shape2E=shape2E, 
  col=c("green", "red"), cex.sub=.8)
plot(res)
```

---

**plotBDP2**  
*Plots*

Description

Output of desired plots
Usage

plotBDP2(x = c("n", "k", "ptrue", "cE", "cF"),
        y = c("Prob0Successes", "PostProb0or1Successes", "bFbE",
             "PEcall_p0_p1", "PEstop_p0_p1",
             "PFstopEcall", "PFstopEstop",
             "PEcall", "PEstop", "PFstop", "PFstopEstop",
             "ExpectedNumber",
             "PredictivePower"),
        n, interim.at, ptrue,
        pF, cF, pE, cE, p0, p1, Estop=FALSE,
        shape1F, shape2F, shape1E = NULL, shape2E = NULL,
        col = c("green", "red"), cex.legend=1, add = FALSE,
        show=TRUE, progress = FALSE, ...)

Arguments

x character string specifying what is given by the x axis
- "n" for number of patients at final or at first interim, depending on plot
- "ptrue" for the true response rate
- "k" number of successes at interim (only for y="PredictivePower")
- "cE" for the critical level of posterior probabilities used for declaring efficacy
- "cF" for the critical level of posterior probabilities used for declaring futility

y character string specifying what is given by the y axis
- "Prob0Successes" for plot of probability of 0 successes out of n at first interim, i.e. (1-p)^n. Two curves are generated: one for p0 and one for p1. Choose x="n" and set n to a vector of number patients at first interim.
- "PostProb0or1Successes" generates two curves of posterior probability that response rate exceeds cF. One given 0 successes and one given 1 success observed in n, i.e. P(p>pF| 0 successes out of n) and P(p>pF| 1 success out of n). Choose x="n" and set n to a vector of number patients at first interim.
- "bFbE" for plot of boundaries for futility bF and for efficacy bE in terms of number of successes per n number of patients. Futility stop if number of successes <= bF, call efficacy if number of successes >= bE. Choose x="n" and set n to the maximal number of patients (not a vector).
- "PEcall_p0_p1" for plot of probability to call efficacy at final (i.e. P(p>pE|Data)>=cE), evaluated for data generated with control response rate p0 (corresponds to type I error) and for data generated with target response rate p1 (corresponds to power) for varying number of patients at final. Choose x="n" and set n to a vector of number patients at final.
- "PEstop_p0_p1" as above but with stopping for efficacy instead of calling efficacy
- "PFstopEcall" for plotting operating characteristics for a given response rate as a function of number of patients at final, n. Shows one curve (default: in red) for the probability of stopping for futility up to final analysis and one curve (default: in green) for the probability of calling efficacy at final
analysis. For the setting ptrue=p0, the curves show the probability of true stopping (default: in red) and type I error (default: in green). For the setting ptrue=p1, the curves show the probability of false stopping (default: in red) and power (default: in green). Choose x="n" and set n to a vector of number patients at final.

- "PFstopEstop" as above but with stopping for efficacy instead of calling efficacy
- "PEcall" for plot of probability to call efficacy at final (i.e. P(p>pElData)>=cE).
  - For x="ptrue" then this is the power function.
  - For x="cE" this gives plots of probability to call efficacy at final, evaluated for data generated with control response rate p0 (corresponds to type I error) and for data generated with target response rate p1 (corresponds to power).
- "PEstop"
  - For x="ptrue" then this is the power function.
  - For x="cE" this gives plots of probability to call efficacy at final, evaluated for data generated with control response rate p0 (corresponds to type I error) and for data generated with target response rate p1 (corresponds to power).
- "PFstop" for plot of cumulative probability to stop for futility up to final.
  - For x="ptrue" this gives the futility stopping probability as function of ptrue.
  - For x="cF" this gives 2 curves, evaluated for data generated with control response rate p0 (corresponds to true stopping probability, default: in green) and for data generated with target response rate p1 (corresponds to false stopping probability, default: in red).
- "ExpectedNumber" for expected number of patients in the trial. Choose x="ptrue". Takes stopping for efficacy into account if Estop=TRUE
- "PredictivePower" for predictive power (only for x="k")

n sample size at the final analysis, vector if x="n"
interim.at vector of sample sizes at the interim analyses
ptrue true (assumed) response rate used for simulating the trial, vector if x="ptrue"
pF response rate used for the futility criterion P(p>pFlData) < cF (may be identical to pE)
cF critical level of posterior probabilities used for declaring futility, vector if x="cF"
pE response rate used for the efficacy criterion P(p>pElData) >= cE
CE critical level of posterior probabilities used for declaring efficacy, vector if x="cE"
p0 response rate corresponding to H0
p1 response rate corresponding to H1 (p1 > p0)
shape1F first parameter of the Beta prior for futility analysis
shape2F second parameter of the Beta prior for futility analysis
shape1E first parameter of the Beta prior for efficacy analysis
plotBDP2

shape2E  second parameter of the Beta prior for efficacy analysis
Estop   Stop for efficacy? Defaults to FALSE. Only relevant if y="ExpectedNumber".
col     line color, for some plots vector of length 2.
add     add line to existing plot. Only supported if x="ptrue"
show   show plot (otherwise computed objects are invisibly returned)
progress only used by shiny app
cex.legend size of legend text relative to cex
... additional arguments passed to plot.default()

References

Examples

# See vignette for more details and examples
pF=0.3
pE=0.12
shape1F=0.3
shape2F=0.7
shape1E=0.12
shape2E=0.88
cF=0.01
cE=0.9
nvec=c(18:TPI
interimNat=c(1:PLRPLSPI
C type I error and probability of true stopping for the uninteresting response rate
ptrue=0.12
plotBDP2(x="n", y="PFstopEcall",
   n =nvec, interim.at = interim.at,
   pF=pF,cF=cF,pE=pE,cE=cE,ptrue=ptrue,
   shape1F=shape1F,shape2F=shape2F,shape1E=shape1E,shape2E=shape2E)

# Power and probability of false stopping for the target response rate.
ptrue=0.3
plotBDP2(x="n", y="PFstopEcall",
   n =nvec, interim.at = interim.at,
   pF=pF,cF=cF,pE=pE,cE=cE,ptrue=ptrue,
   shape1F=shape1F,shape2F=shape2F,shape1E=shape1E,shape2E=shape2E)
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