A Rotating Grater-like Cutting Tool to Remove Hard Cemented Deposits in Heart Blood Vessels without Damaging Soft Vessel Walls

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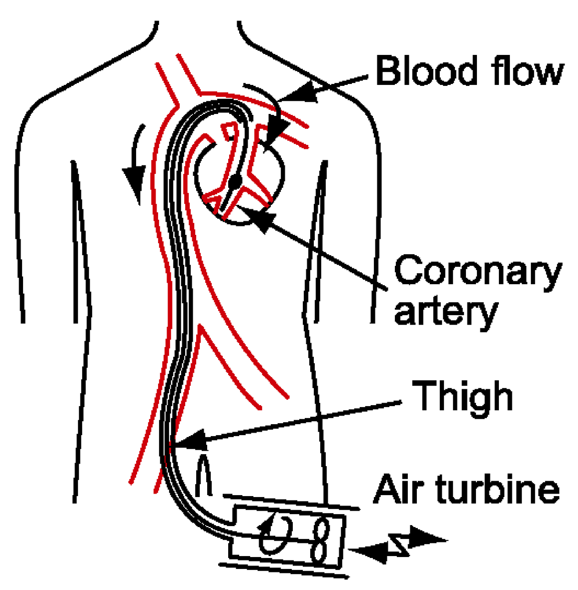
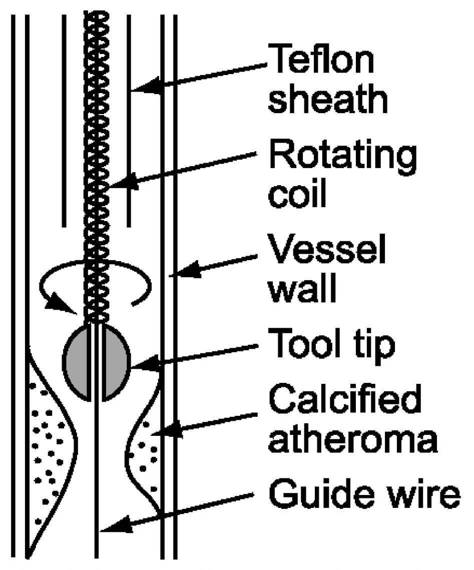
Background

PTCRA (percutaneous transluminal coronary rotational atherectomy)





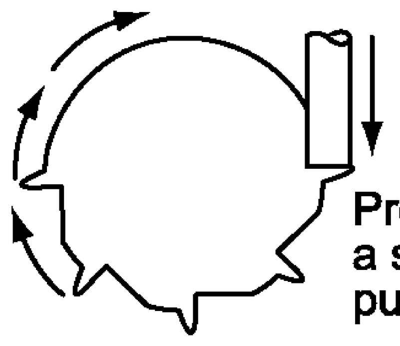
Ground off by a diamond grains metal-bonded grinding tool, "Rotablator (Boston Scientific Corp.)"

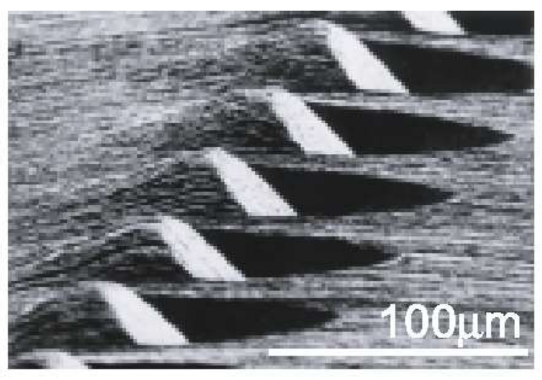
Design of rotating grater-like cutting tool

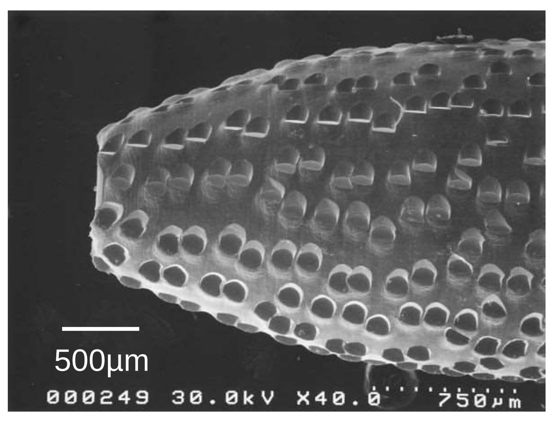
- FR1: Remove hard cemented deposits, i.e. calcified atheroma.
- FR2: Do not damage the soft vessel walls.
- FR3: Do not let tool tips wear or fall off.
- FR4: Finish cutting the calcified atheroma within 30 seconds or less.
- FR5: Be visible with X-ray.
- FR6: Stop the cutting upon excessive cutting force.

(FR: Functional Requirement)

Fabrication of the grater tool







Bullet shaped tool (Steel)

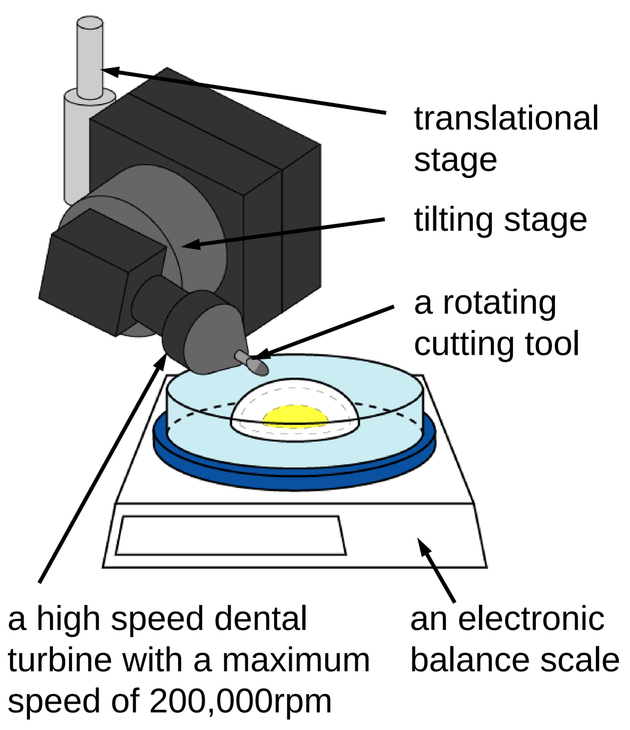
Type	#	material	height [m]	pitch [mm]	orientation
Grater height	1	anodized aluminum	30	0.2	dent first
	2		20	0.2	dent first
	3		20	0.2	bulge first
	4		5	0.2	bulge first
	5		5	0.1	bulge first
	6	steel*1	20	0.2	bulge first
	7	brass*2	20	0.2	dent first
	8	brass	-20	0.2	dent only
	9	brass	0	-	flat
Diamond height	10	nickel plated brass	30	-	-
	11		20	-	-
	12		15	-	-
	13		10	-	used in surg.
	14		7	-	-

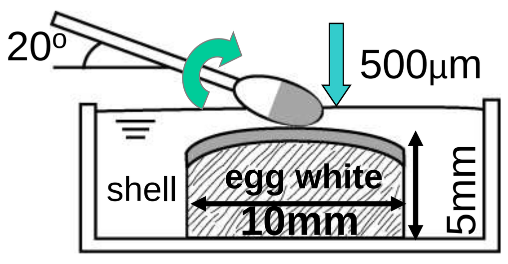
*1 quenched tool steel *2 nickel plated brass

Table 1: Used tools in the experiments.

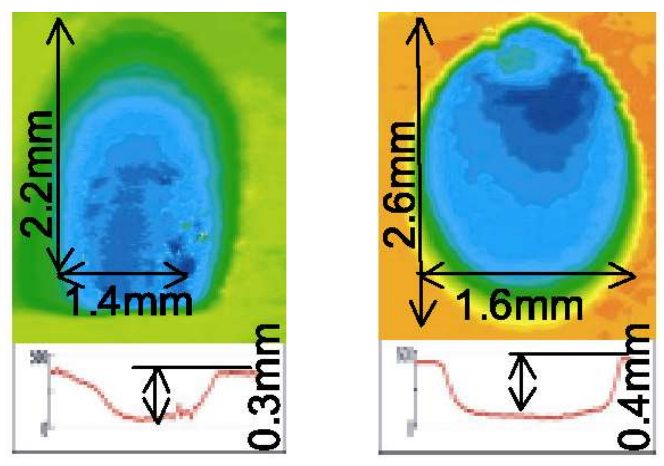
Experiments

Experimental set up





The tool in rotating is pressed down to 500μm against the egg underwater



(a) w/ grater tool (b) w/ diamond tool

Best tools for cutting eggshell

Type	#	material	height [m]	pitch [mm]	orientation	#	removal rate of eggshell cutting (FR1&FR5)	scratch on cut egg white (FR2)	used tool surface aft. 3min. eggshell cutting (FR3)
Grater height	**1**	anodized aluminum	**30**	**0.2**	**dent first**	1	**0.095 [mm³/s]**	visible	**no wear**
	2		20	0.2	dent first	2	0.089	visible	no wear
	3		**20**	**0.2**	**bulge first**	3	**0.074**	**not visible**	**no wear**
	4		5	0.2	bulge first	4	0.010	not visible	no wear
	5		**5**	**0.1**	**bulge first**	5	0.025	slightly visible	**no wear**
	6	steel*1	20	0.2	bulge first	6	0.069	not visible	local wear on bulges
	7	brass*2	20	0.2	dent first	7	0.008	visible	hard wear on bulges
	8	brass	-20	0.2	dent only	8	0	slightly visible	-
	9	brass	0	-	flat	9	0	not visible	-
Diamond height	**10**	nickel plated brass	**30**	-	-	10	**0.15**	visible	-
	11		**20**	-	-	11	**0.13**	visible	-
	12		**15**	-	-	12	**0.10**	visible	-
	13		10	-	used in surg.	13	0.087	not visible	particles dropped
	14		**7**	-	-	14	**0.072**	**not visible**	**particles dropped**

*1 quenched tool steel *2 nickel plated brass

Table 1: Used tools in the experiments. Table 2: Experimental result (screening columns meet the FRs).

Grater : 20μm high is the best
Diamond: 7μm high is the best

Water flow influence

Type	#	material	height [m]	pitch [mm]	orientation	#	removal rate of eggshell cutting (FR1&FR5)	scratch on cut egg white (FR2)	used tool surface aft. 3min. eggshell cutting (FR3)
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	3		20	0.2	bulge first	3	0.074	not visible	no wear
	4		5	0.2	bulge first	4	0.010	not visible	no wear
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	7	brass*2	20	0.2	dent first	7	0.008	visible	hard wear on bulges
	8	**brass**	**-20**	**0.2**	**dent only**	8	0	slightly visible	-
	9	**brass**	**0**	**-**	**flat**	9	0	**not visible**	-
Diamond height	10	nickel plated brass	30	-	-	10	0.15	visible	-
	11		20	-	-	11	0.13	visible	-
	12		15	-	-	12	0.10	visible	-
	13		10	-	used in surg.	13	0.087	not visible	particles dropped
	14		7	-	-	14	0.072	not visible	particles dropped

Water flow doesn't cut the shell.

not visible at 200,000 rpm → visible at 7,000 rpm

Water flow prevents the egg white scratch.

Ware of the tool

Type	#	material	height [m]	pitch [mm]	orientation	#	removal rate of eggshell cutting (FR1&FR5)	scratch on cut egg white (FR2)	used tool surface aft. 3min. eggshell cutting (FR3)
Grater height	1	anodized aluminum	30	0.2	dent first	1	0.095 [mm³/s]	visible	no wear
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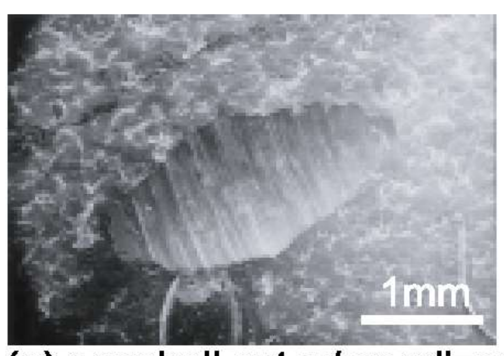
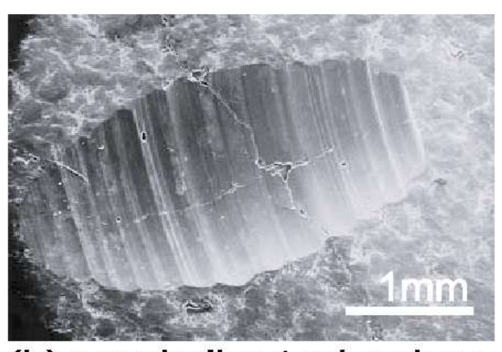
Diamond height	10	nickel plated brass	30	-	-	10	0.15	visible	-
	11		20	-	-	11	0.13	visible	-
	12		15	-	-	12	0.10	visible	-
	13		10	-	used in surg.	13	0.087	not visible	particles dropped
	14		7	-	-	14	0.072	not visible	particles dropped

Anodized aluminum tool has no wear.

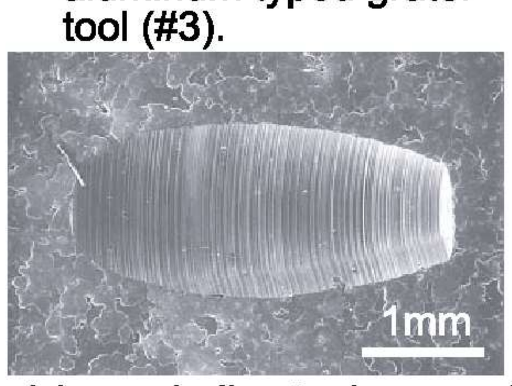
Surfaces of cut workpieces



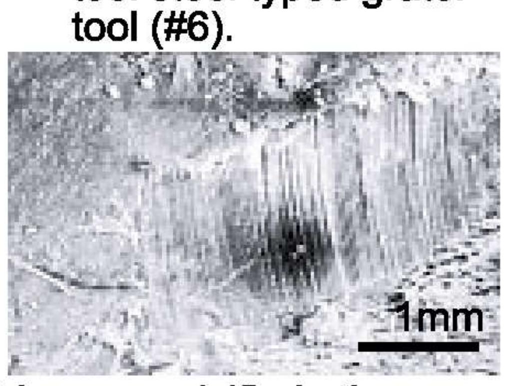
(a) eggshell cut w/ anodized aluminum typed grater tool (#3).



(b) eggshell cut w/ carbon tool steel typed grater tool (#6).



(c) eggshell cut w/ diamond tool (#13).



(d) human calcified atheroma cut w/ a diamond tool [6].

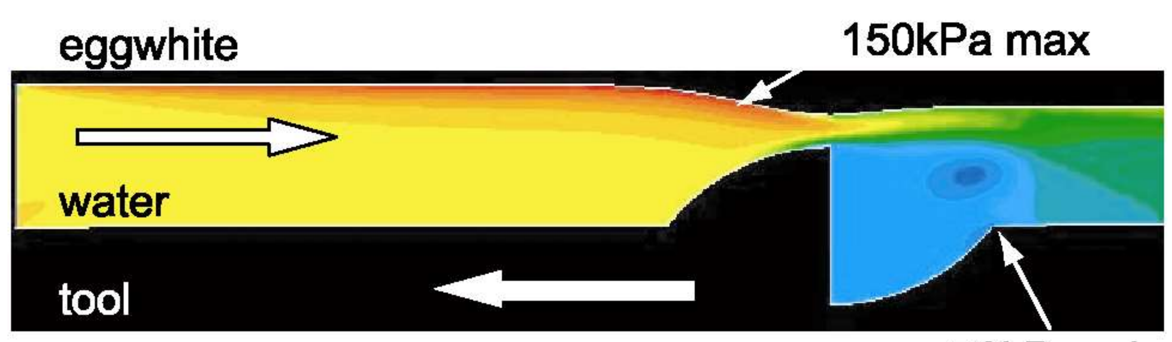
Calculated gap heights ($H_{min}R$) by Herrebrugh equations.

tool R=1mm, 200,000rpm E=100GPa, ν=0.2 down force w=0.2N, L=2mm	$H_{min}R^{*1}$ at line contact	$H_{min}R^{*2}$ at point contact
(a) eggshell E=10GPa ν=0.2 (water, tool)	0.065μm	0.019μm
(b) egg white E=20kPa ν=0.4 (water, tool)	**10μm**	**5.0μm**
(c) egg white E=20kPa ν=0.4 (air, tool)	0.93μm	0.37μm

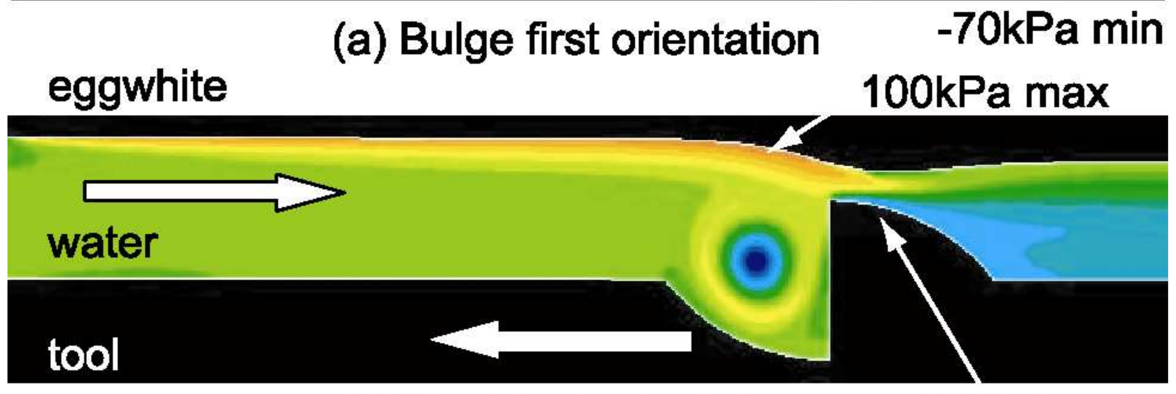
*1 $H_{min}=3.10\,U^{0.6}W^{-0.2}$ $U=\eta u/(ER)$, $W=w/(ERL)$
*2 $H_{min}=2.80\,U^{0.65}W^{-0.21}$ $U=\eta u/(ER)$, $W=w/(ER^2)$
η=0.001Pa*sec (water), 0.000018Pa*sec (air)

Young's ratio : 300kPa of a live pig blood vessel, 20 to 50kPa of boiled egg white.

Simulated pressures on grater tools



(a) Bulge first orientation



(b) Dent first orientation